ECONOMIC GEOLOGY

VOL. XXXVI NOVEMBER, 1941 No. 7

COMMENTS ON THE ORIGIN AND MAJOR STRUCTURAL CONTROL OF IGNEOUS ROCKS AND RELATED MINERAL DEPOSITS.

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INTRODUCTION.

THE belief that ores were derived from magmatic sources, although advocated long ago, gained special recognition in the period 1901–1905. Probably the outstanding contribution to this belief was Lindgren's report on the Clifton-Morenci district, Arizona.[2] In this report it was shown that the monzonite porphyry associated with the ore was not appreciably altered and that the ore deposits at and near the igneous contact had evidently been deposited by

[1] Address of the retiring president of the Society of Economic Geologists, presented at the annual meeting of the Society in New York, N. Y., February 18, 1941. Published by permission of the Director, Geological Survey, United States Department of the Interior.

[2] Lindgren, Waldemar: The copper deposits of the Clifton-Morenci district, Arizona. U. S. Geol. Surv. Prof. Pap. 43: 19–23, 1905.

solutions expelled from the porphyry during its crystallization. For several years after 1905 there was a tendency to follow the new fashion and attribute the sources of ores to the nearest masses of intrusive rock that happened to be exposed, whether evidence in support of the idea was adequate or not. As geologic study became more critical, however, and as the deepening of mines afforded more evidence, the complexity of the problems related to the structural control and origin of ore deposits became increasingly appreciated, and in the words of McLaughlin [3] the tendency grew to push the source to depths "more safely out of reach." The skeptic, therefore, may wonder to what extent the interpretations made several years ago would be modified if the deposits in question were to be restudied in the light of fundamental information now available.

My own variety of skepticism may be attributed largely to the fact that in New England, where I was introduced to geology, there are many masses of intrusive igneous rock, large and small, but no ore deposits big enough to cause excitement; also to the fact that in the few contact-metamorphic deposits that I have studied in the West the sulphide minerals were deposited later than gangue minerals whose origin could be directly attributed to emanations from a crystallizing igneous mass. My early work in New England also developed an interest in the part played by intrusive rocks in regional metamorphism and in mountain building, and, supplemented by later work elsewhere, led me as early as 1915 to wonder to what extent all igneous processes and related processes of mineral deposition might be correlated into a definite sequence or cycle and coordinated with the development of regional and local structure. Such an idea to be satisfactorily demonstrated would obviously call for years of concentrated research, but, as I was sentenced to administrative work 23 years ago and as the sentence is still being served, the idea has received only casual attention. In the meantime so much fundamental information bearing on the subject in some degree has been assembled

[3] McLaughlin, Donald: Fields of the economic geologists widen and their technique improves. Min. and Met. 21: 5, 1940.

and critically analyzed as to encourage the hope that, if I could keep still a little longer, the whole problem might be solved for me; but something is expected of a retiring president, and I therefore risk some comments on the subject now.

SEQUENCE OF STRUCTURAL AND IGNEOUS PROCESSES.

Two publications that have been very helpful in affording a general structural framework to which pertinent observations could be fitted are those by Vening Meinesz and his colleagues on the structure of the East Indies in the light of gravimetric studies [4] and by Bucher on the deformation of the earth's crust.[5] These authors, approaching the general problem from different viewpoints, are in remarkably close, though not complete agreement. To quote Bucher,[6] "The typical orogenic cycle begins with geosynclinal depression and ends with a major uplift. The interval between these limiting events comprises two phases. The first phase is one essentially of quiet sinking, only occasionally interrupted by uplifts; the second phase consists of crustal foldings separated by diminishing epochs of renewed geosynclinal sinking." In the East Indies the original depression is of crescentic outline; the stronger component of compression during the period of folding was directed toward the concave side of the crescent and gave rise to complementary shearing and tensional forces on that side. The major uplift that follows the folding is of long duration and is accompanied by repeated faulting and minor folding. Strong earthquakes take place within the crescentic zone of intense compression, and volcanoes are localized in a zone that parallels the crescent and lies from 100 to 200 kilometers from its concave side. This outline of structure in the East Indies accords well with Bucher's interpretation of structure in the Appalachian and Rocky Mountain provinces, to which my remarks will be mainly directed.

[4] Kuenen, P. H., Umbgrove, J. H. F., and Vening Meinesz, F. A.: Gravity geology and morphology of the East Indian Archipelago. Publication of the Netherlands Geodetic Commission, pp. 112–136, Delft, 1934.

[5] Bucher, W. H.: The deformation of the earth's crust. Princeton Univ. Press, Princeton, N. J., 1933.

[6] Idem, p. 126.

Without taking time now to review the inferred fundamental causes of this succession of events, the correlation of igneous activity with structural processes may be briefly summarized. Bucher attributes the origin of large furrows or geosynclines in which sedimentation took place to the thinning of the earth's crust by tensional forces. Whenever tensional forces were sufficient the crust became broken by fissure zones which tapped the underlying ferromagnesian material and permitted it to rise in the form of dikes, sills, or surface flows. Whether we favor the derivation of basalt directly from a basaltic substratum as suggested by Daly,[7] or from liquid squeezed from a crystallizing peridotite as suggested by Bowen,[8] may make little difference, so long as we bear in mind that the material was ferromagnesian and came from beneath the crust. Where this subcrustal material could reach the surface rapidly during this early period of tension and subsidence it would undergo little or no differentiation; where its upward progress was impeded it might react with the crust and undergo the same general process of differentiation that characterized the late period of tension and uplift, though to a smaller degree, as conditions for extensive differentiation were less favorable.

When the long period of dominant subsidence and sedimentation ended, and the cause of its ending is obscure, tension gave way to compression, which forced the thick crust on either side against the thinned zone or furrow with its overlying sediments. Rocks in and immediately below the furrow became intensely compressed and buckled; those in its lower part were forced downward and those in the uppermost part bulged upward and outward in a series of complex folds modified by thrust faults. This bulging opposed the encroachment of the upper part of the adjoining crust, which accordingly broke along a series of low-angle planes which Vening Meinesz [9] aptly terms underthrusts.

During the early stages of this period of intense compression

[7] Daly, R. A.: Igneous rocks and the depths of the earth. McGraw-Hill, New York, 1933. Pp. 177, 186–189, 197, 199–200, 240.

[8] Bowen, N. L.: The evolution of igneous rocks. Princeton Univ. Press, Princeton, N. J., 1928. P. 319.

[9] Op. cit., p. 131.

brief moments of relaxation or the development of local tensional stresses may have allowed the further intrusion of ferromagnesian rocks from the subcrust. Such conditions could account for masses of peridotite or serpentine like those in the Sierra Nevada, Calif.,[10] and in the Barre quadrangle, Vt.,[11] which were intruded between early and late stages of intense compression.

After compression and consequent folding had approached or reached a maximum large granitic masses were intruded. Bucher [12] suggests that granitic intrusion may have taken place in several stages, the earliest conforming to the schistosity of the deformed rocks and the later cutting across it. My own local experience is in complete accord with this general suggestion. Bucher, however, feels that "large concordant acid intrusives in folded sediments are widespread only in early pre-Cambrian terranes." [13] . . . "It is as if in later times granitic magmas had not been able to reach the sedimentary mantle in quantity during the earlier compressive epochs of an orogenic phase or perhaps did not form at all." [14] This more specific suggestion may also be generally true, but, as the results of detailed work accumulate, particularly in New England and the southeastern States, it may become recognized that granites were intruded into Paleozoic rocks during the Appalachian revolution while intense folding was still in progress. In eastern Connecticut, for example,[15] two if not three stages of granite intrusion took place under sufficient pressure to develop primary gneissic structure. This intrusion was accompanied by pegmatite and by volatile material that in-

[10] Knopf, Adolph: The Mother Lode system of California. U. S. Geol. Surv. Prof. Pap. 157: 18–20, 1929.

Ferguson, H. G.: Gold quartz veins of the Alleghany district, California. U. S. Geol. Surv. Prof. Pap. 172: 21, 1932.

[11] Jahns, R. H.: Oral communication based on detailed field work in 1939 and 1940.

[12] Op. cit., p. 290.

[13] Idem, p. 294.

[14] Idem, p. 295.

[15] Loughlin, G. F.: The gabbros and associated rocks at Preston, Conn. U. S. Geol. Surv. Bull. 492: 37, 43, 57, 129–135, 1912.

Martin, Laura Hatch: The geology of the Stonington region, Conn. Conn. State Geol. and Nat. Hist. Surv. Bull. 33: 22, 36–46, 1925.

vaded the adjoining Carboniferous and older rocks and aided in their conversion into schist and injection gneiss. In other words, the granite invasions had much to do with regional metamorphism, as was shown by Barrell,[16] who contrasted the metamorphosed Paleozoic rocks in Connecticut with the unmetamorphosed though thoroughly folded equivalent rocks in Pennsylvania.

To correlate this process with the general structural framework it may be inferred that the invading granite, taking advantage of such zones of weakness as it could find, moved along and thereby obliterated zones of underthrusting. From these main courses of invasion it spread into adjoining folded rock. The invaded rock, rendered incompetent through recrystallization, buckled into overturns whose axial planes commonly dipped at moderate angles and whose schistosity essentially coincided with original bedding. No fractures could persist in the invaded rock under these conditions, and the invading granite or granitic solutions therefore followed the directions of schistosity and formed sill-like masses.

These gneissic granites are cut by stocks and dikes of even-grained granite, which correspond to those recognized by Bucher [17] in the southeastern States as having been intruded during the tensional period that followed that of major compression. This tensional period was accompanied by vertical uplift of the region. These stocks or small batholiths are also accompanied by pegmatite. They lie typically on the concave side of the belt of intense folding—the side from which the dominant compressive force was active. The localization of these stock-like masses invites further study, but it seems clear that the fissuring that accompanied vertical uplift must have aided the rise of granitic material that was still fluid. How high this fluid material could rise would depend on structural conditions. In some places it failed to get through the zone of gneiss and schist, and in such places Bucher's suggestion that it "perhaps did not form at all" is justified; elsewhere it may have risen well above the schistose zone and penetrated rocks that are quite free from metamorphism except at the

[16] Barrell, Joseph: Relation of subjacent invasion to regional metamorphism. Am. Jour. Sci., 5th ser., 1: 1–19, 174–186, 255–267, 1921.

[17] Bucher, W. H.: Op. cit., pp. 274–276.

immediate contacts with the granite stocks. The volcanoes that parallel the belt of intense compression in the East Indies may be surface expressions of similar igneous activity.

It is noteworthy that the rocks intruded during and shortly after the period of major compression were granitic and were evidently derived from the granitic crust, particularly the part that had been buckled downward and thereby subjected to abnormally high temperature. The vertical uplift and fissuring that followed the period of compression, however, permitted subcrustal material to rise and differentiate. The extent of differentiation presumably depended upon whether the subcrustal material rose rapidly along major fissure zones and formed essentially undifferentiated basaltic flows, dikes, and sills, or whether it became trapped long enough to undergo fractional crystallization and perhaps also react with the heated rocks of the crust.

So far as I recall, the only intrusive rocks in the Appalachian province that are clearly younger than the cross-cutting granites are the dikes and sills of Triassic diabase. The larger of these, for example, the great sill of the Palisades, N. J.,[18] and the dike at Goose Creek, Va.,[19] show effects of local differentiation, which are helpful to some extent but do not present all the information essential to an appreciation of the question at hand.

To round out the story information will be drawn from a small part of the Rocky Mountain province. The Rocky Mountain Front Range, which extends northward from New Mexico, consists of a steplike row of crescentic segments. One of these, the Sangre de Cristo Mountains, represents a zone of intense compression in which gneissic granitic rocks have invaded Carboniferous strata and converted them into schist, as shown by Burbank and Goddard.[20] On the concave zone of the belt lies the great San

[18] Walker, Frederick: Differentiation of the Palisade diabase. G. S. A. Bull. 51: 1092–1094, 1940.

[19] Shannon, E. V.: The mineralogy and petrology of intrusive diabase at Goose Creek, Loudoun County, Virginia. U. S. Nat. Mus. Proc. No. 2539 60: 1–86, 1924.

[20] Burbank, W. S., and Goddard, E. N.: Thrusting in Huerfano Park, Colo., and related problems of orogeny in the Sangre de Cristo Mountains. G. S. A. Bull. 48: 952–976, 1937.

Juan volcanic field, which largely obscures the structure of the underlying sedimentary rocks, but significant information on uplift and faulting subsequent to compression has been obtained by Burbank,[21] especially during his thorough study in the vicinity of Ouray.

The igneous history of the region subsequent to compression points to a long period of uplift, differentiation, intrusion, and extrusion interrupted by a quiet interval during which considerable erosion took place. Before this interval some minor folding took place, which may be compared with the minor folding cited by Umbgrove in the East Indies.[22] Major fractures formed during and just after this folding opened the way for the rise of monzonite which spread mainly as laccolithic masses beneath the thick Mancos shale. Intrusion was followed by the first of two periods of ore deposition.

After the quiet interval, during which the laccoliths were exposed, the great eruptions of San Juan volcanic rocks took place. Late in the volcanic history extensive faulting took place and accounted for the subsidence of a great triangular block between Ouray and Silverton. Adjustments along and near this block are too many and complicated to be recounted here, except to say that stocks and pipe-like masses of monzonitic rock and of gabbroic rock with monzonitic facies were intruded along the margins of the sunken block and at a few other favorable spots, and that dikes radiated from these intrusive centers. The intrusion of these stocks and dikes was followed by the second period of ore deposi-

[21] Burbank, W. S.: Revision of geologic structure and stratigraphy in the Ouray district of Colorado, and its bearing on ore deposition. Colo. Sci. Soc. Proc. 12: 151–232, 1930.

——: Vein systems of the Arrastre Basin and regional geologic structure in the Silverton and Telluride quadrangles, Colorado. Colo. Sci. Soc. Proc. 13: 135–314, 1933.

——: Structural control of ore deposition, Uncompahgre district, Ouray County, Colo. U. S. Geol. Surv. Bull. 906–E: 197–200, 1941.

——: Structural control of ore deposits in the Red Mountain, Sneffels, and Telluride districts, in the San Juan Mountains, Colo. Colo. Sci. Soc. Proc. (in preparation), 1941.

[22] Kuenen, P. H., Umbgrove, J. H. F., and Vening Meinesz, F. A.: Op. cit., pp. 142–149.

tion. After this period further uplift accompanied by faulting marked the closing stage of the igneous cycle.

In the Colorado Front Range, the central part of which has been thoroughly studied by Lovering and Goddard,[23] deformation was less intense than in the Sangre de Cristo Mountains. No gneissoid intrusive granite of post-Carboniferous or Laramide age is known there, but the region between the steeply-dipping reverse faults near Golden on the east and the Williams underthrust on the west indicate an upward bulging. This bulging and longitudinal stretching may have induced transverse tension, which was further developed during the tensional period of uplift that followed and gave rise to the great transverse fissure zone or "mineral belt" along which stocks, dikes, and veins were formed. This "mineral belt," however, is part of the great complex zone, designated the Porphyry Belt by Ball, that extends southwestward across the mountainous part of the State [24] and is controlled in part by structural factors inherited from pre-Cambrian and particularly Paleozoic processes;[25] in short, the "mineral belt" cannot be fully explained as the result of Laramide and later processes, although its Laramide stage of development was directly concerned with the localization of intrusive rocks and related mineral deposits.

To cite regions still farther west might reinforce the idea of the igneous cycle by duplication of evidence, and might elaborate or modify it to fit regions where deformation has been still less intense; but the story would be unnecessarily lengthened. It will suffice here to say that, although the latest stages of the cycle are

[23] Lovering, T. S.: Geologic history of the Front Range, Colo. Colo. Sci. Soc. Proc. 12: 93–109, 1929.

——: Geology and ore deposits of the Breckenridge mining district, Colo. U. S. Geol. Surv. Prof. Pap. 176: 17–23, 1934.

——: Geology and ore deposits of the Montezuma quadrangle, Colo. U. S. Geol. Surv. Prof. Pap. 178: 43–51, 1935.

——: Geology of the Front Range mineral belt, Colo. Proc. Colo. Sci. Soc. 14: 46–47, 1938.

[24] Spurr, J. E., Garrey, G. H., and Ball, S. H.: Economic geology of the Georgetown quadrangle, Colo. U. S. Geol. Surv. Prof. Pap. 63: 70, pl. 11, 1908.

[25] Burbank, W. S.: Relation of Paleozoic and Mesozoic sedimentation to Cretaceous-Tertiary igneous activity and the development of tectonic features in Colorado. Ore Deposits of the Western States (Lindgren Volume), pp. 277–301, 1933.

much in evidence, granites intruded during the main stage of compression may not have broken through the pre-Cambrian basement, and their part in the cycle is therefore unknown.

The derivation of such immense quantities of volcanic rock as are represented in the San Juan volcanic field involves additional speculative problems that could not be adequately considered in a few minutes even if I felt competent to consider them. It may tax the imagination too much to regard them as differentiates of the basaltic substratum or even as products of reaction between material from the substratum and the overlying granitic crust. They may be attributed to the remelting of crustal material within the crust, aided perhaps by volatile or hyperfusible material, wherever profound fissuring and release of pressure made the process possible. Whatever the exact process was, the significant points to bear in mind at present are that the eruptions took place during the prolonged period of uplift and fissuring, were accompanied by volatile mineralizers but not by appreciable quantities of ore-forming solutions, and were followed by monzonitic and gabbroic intrusions, which in turn were followed by ore deposition. These late intrusive rocks and the ore-forming solutions were evidently derived from beneath the volcanic reservoirs and therefore were more closely related to the basaltic substratum.

RELATION BETWEEN PROCESSES OF MINERALIZATION AND IGNEOUS INTRUSION.

In accordance with the foregoing remarks, processes of mineralization may be considered in three groups: those associated with ferromagnesian rocks intruded before or during early stages of regional compression; those associated with granitic rocks intruded during and soon after the closing stages of major compression; and those associated with monzonitic and related differentiates intruded during the prolonged period of uplift and faulting that followed the main period of compression. The last group could be subdivided to correspond to the two stages of mineralization that are known to have taken place at Ouray and at certain other districts throughout the West, but no effort will be made to do so now.

Deposits Associated with Ferromagnesian Rocks Intruded Before or During the Early Stages of Regional Compression.—Evidence that basaltic eruptions were accompanied and closely followed by appreciable quantities of mineralizing elements is amply recorded in deposits around active volcanoes and in the minerals that fill vesicles and other openings in lava flows, but the varieties of metalliferous deposits directly associated with basaltic flows are essentially restricted to native copper and its sulphides. That determinable quantities of copper are present in unaltered basalt is well known, and it is conceivable that small deposits of copper, calcite, and zeolites in basalt may have been leached from the rock and redeposited by solutions derived from the same source as the basalt. The extent to which these minerals have been concentrated would depend on the fracture pattern that could permit concentration or dissipation of the circulating solutions.

Whether large copper deposits in basalt, like those of the Lake Superior country, can be explained by such leaching and reconcentration is extremely doubtful, although the process may have contributed to some extent. It is also likely that they were formed after periods of compression had deformed the basalt. If leaching and reconcentration seem inadequate, appeal must be made to differentiation, whose effects are partly expressed in the different facies of the Duluth gabbro, and to the consequent deep-seated concentration of copper in solution—perhaps a sulphide solution, which according to Vogt's experiments [26] may separate from a basaltic liquid at high temperature. If separation were complete the solution, either through pressure that it could develop itself or through late profound fissuring of regional scope, could rise along any available openings, fissures or bedding planes, and its reaction with the oxidized vesicular tops of lava beds could account for the deposition of native copper instead of sulphides, as shown by Butler and Burbank.[27]

[26] Vogt, J. H. L.: Die Silikatschmelzlösungen, pt. 1, Videnskabs-Selskabets-Skrifter, Math.-Naturv. Klasse, Kristiania, No. 8, 1903.

——: Magmas and igneous ore deposits. ECON. GEOL. 21: 315, 1926.

[27] Butler, B. S., and Burbank, W. S. (with others): The copper deposits of Michigan. U. S. Geol. Surv. Prof. Pap. 144: 129–133.

If separation were not complete a mixture of basaltic and sulphide solution might be tapped, and, if conveniently trapped in its ascent, might form a deposit like that at Sudbury, Ontario, in which the rock material crystallized as norite or gabbro and the copper sulphide, unable to escape, settled to the bottom of the igneous mass or crystallized in available interstices. If separation were complete the copper solution could later rise, impregnate the norite and form deposits in other rocks nearby. The differences of opinion expressed by those who have studied the Sudbury deposit are various and emphatic, and as my acquaintance with such deposits is negligible, I shall say no more. My only impression is that large copper deposits so closely associated with basaltic, gabbroic, or peridotitic rocks may be derived mainly through prolonged though relatively simple differentiation of a ferromagnesian magma and in part through the leaching of ferromagnesian rock by rising solutions.

Similar comments may be made about nickel. R. C. Wells' determinations of the nickel contents of many different kinds of rocks and minerals confirms previous inferences that nickel is also present mainly in ferromagnesian minerals,[28] though in smaller amount than copper. The presence of nickel with copper in deposits of the Sudbury type, therefore, is not surprising. What became of the nickel in the Lake Superior deposits is "one of those questions," as very little nickel has been detected in them.[29] Small deposits of nickel minerals like those of copper may be attributed to the leaching of ferromagnesian rock soon or long after its intrusion. Whether the origin and major structural control of nickel-cobalt-silver deposits in the Cobalt district can be correlated with this notion is another question that I shall leave to our Canadian friends; speculation about them would be simply an indoor sport for me. The close association of chromium, platinum, and nickel with rocks of the peridotite group and the variations in features of the deposits, especially those of chromite, are

[28] Wells, R. C.: Relative abundance of nickel in the earth's crust. U. S. Geol. Surv. Prof. Pap. 197 (in preparation).

[29] Butler, B. S., and Burbank, W. S.: Op. cit., p. 38.

subject to similiar consideration and no time will be taken to review them now.

Deposits Associated with Granitic Rocks Intruded During or Soon After the Closing Stages of Major Compression.—The amount of volatile matter that accompanied granite intrusions, both during and after the main compressive period was very great. Part of this volatile matter is thought to have acted as an advance guard and to have had much to do with the conversion of sedimentary and old volcanic rocks into schists. This thought is supported in some degree by Griggs' recent experiments [30] in which compression at high temperature, even in the presence of water but in the absence of such critical elements as fluorine failed to produce the minerals found in nature. It is further supported by field evidence that these older rocks became impregnated or even replaced by minerals typical of granite before distinct sill-like bodies of granite were intruded.

Additional quantities of volatile matter of generally similar composition were active at the close of each stage of granitic intrusion, both during and after the main period of compression, forming pegmatite and related silicate deposits. Some pegmatite masses are small and irregular and appear to be the products of strictly local concentrations of volatile matter; some, dike-like in form and arranged in step-like groups, grade into the adjacent granite and cannot be correlated with distinct fissures, although fissuring that took place before the granite had completely solidified evidently controlled their form and distribution; others occur in linear groups or zones of relatively great length as if they were derived from volatile matter that had collected at some depth and became released by the fissuring of thoroughly solidified rock, either along longitudinal zones related to the course followed by the granite itself or along transverse zones of tension.

There is nothing in the mode of occurrence or composition of these pegmatites and related materials to oppose the generally accepted idea that they have been derived from the granite and not

[30] Griggs, David: Experimental flow of rocks under conditions favoring recrystallization. G. S. A. Bull. 51: 1002, 1021, 1940. (Also oral discussion.)

from some deeper source. They consist mainly of minerals common to the related granites and prove that these minerals were stable during the pegmatitic as well as the granitic stage of intrusion. For that reason pegmatitic solutions that invaded rocks other than granite were able to replace or cause the reworking of the minerals of those rocks which thus became converted in some degree to replacement granites.

In some places further selective concentration of mineralizing elements took place at depth, but within the granite, and recurrent disturbance along pegmatite zones permitted the attack and partial replacement of ordinary granite pegmatite by such minerals as tourmaline, beryl, and spodumene—nearly all of them silicates, although phosphates and certain other compounds were also formed. Metallic oxides and sulphides, however, are so scarce in pegmatites that it is difficult to picture commercial deposits of them as being closely related to these emanations from granitic magma.

The tin oxide, cassiterite, comes to mind immediately as an outstanding exception, but in the United States the number and sizes of cassiterite deposits are such that the exception does not stand out very far; furthermore, the position of cassiterite in the pegmatitic sequence differs in different districts. In the Black Hills of South Dakota it is restricted to the earliest of several stages of pegmatite intrusion;[31] at Irish Creek, Va., it is confined to narrow zones of altered granite, or greisen along the margins of quartz veins, which were formed before the cassiterite.[32]

In the Black Range, N. Mex.,[33] cassiterite closely associated with specularite occurs in stringers cutting altered and fractured rhyolite, probably over fissure vents. These occurrences, particularly those in Virginia and New Mexico, suggest that traces of tin in the original rock may have been leached, carried upward, and de-

[31] Smith, W. C., and Page, Lincoln: Tin-bearing pegmatites of the Tinton district, Lawrence County, South Dakota. U. S. Geol. Surv. Bull. 922–T, 1941. (In preparation.)

[32] Koschmann, A. H., Vhay, J. S., and Glass, J. J.: Tin deposits at Irish Creek, Va. (In preparation.)

[33] Fries, Carl, Jr.: Tin deposits of the Black Range, Catron and Sierra Counties, New Mexico (a preliminary report). U. S. Geol. Surv. Bull. 922–M: 355–366, 1940.

posited by solutions rising from deep sources. Rock analyses and spectroscopic records, however, give so little information relative to the presence of tin in unaltered rock, that speculation on the leaching of tin from granitic or other rock versus its concentration in solutions during the crystallization of granite is useless.

Similar remarks may be made about tungsten with special reference to its occurrence as scheelite in silicated limestone at contacts with intrusive granite; however, the occurrence of tungsten remote from intrusive granite masses, for example as ferberite at Nederland, Colo.,[84] and as wolframite and scheelite in pyritic ore at Leadville, Colo.,[85] shows that its concentration is not necessarily associated with the crystallizing of granite close by the deposits, though it does not preclude the leaching of tungsten from granite by solutions rising from a deep source. If as much were known about the distribution of tungsten, tin, zinc, and lead as is known about the distribution of copper, nickel, chromium, barium, and strontium in unaltered igneous rocks, further speculation about leaching might be worth while.

The scarcity of sulphides in direct association with large intrusive granite masses might be attributed to the high temperature within and adjacent to the newly crystallized granite and the escape of the sulphide portions of pegmatitic solutions to higher levels which have been removed by erosion, but the scarcity or absence of appreciable sulphide deposits in the less metamorphosed roof rocks around the upper margins of large granite masses favors the inference that the solutions escaping from even the deeper parts of a crystallizing granite contained little sulphur.

The small pegmatite pipes in the alkalic granite at Quincy,

[84] George, R. D.: The main tungsten area of Boulder County, Colorado, with notes on the intrusive rocks by R. D. Crawford, First report, 1908. Colo. Geol. Surv., pp. 1–103, 1909.

Lovering, T. S.: Tungsten deposits of Boulder County, Colo. U. S. Geol. Surv. Bull. 922–F: 135–148, 1940.

[85] Fitch, R. S., and Loughlin, G. F.: Wolframite and scheelite at Leadville, Colorado. ECON. GEOL. 11: 30–36, 1916.

Emmons, S. F., Irving, J. D., and Loughlin, G. F.: Geology and ore deposits of the Leadville mining district, Colorado. U. S. Geol. Surv. Prof. Pap. 148: 171, 1927.

Mass.,[36] are of particular interest as they have clearly been derived directly from the local granite magma. They consist mainly of coarse-grained minerals essentially identical with those that form the granite but contain central cores of massive quartz in which miarolitic cavities contain a little molybdenite, sphalerite, galena, chalcopyrite, fluorite, octahedrite, ilmenite, and parisite. This assemblage indicates a direct connection between granitic magma and sulphide solutions, but the quantity of sulphides is trivial and lends support to the idea that large metalliferous deposits are products of deep-seated differentiation subsequent to the intrusion of batholiths or stocks.

Molybdenite may be thought of as an exception to this impression, but it is interesting to note that the great deposit at Climax, Colo., although it impregnates pre-Cambrian granite, was deposited during Laramide or early Tertiary time.[37]

The association of gold with granite is of special interest because of W. H. Emmons' conclusion that gold-forming solutions on the whole have been derived from the upper parts of granite batholiths, particularly in cupolas that project into overlying rocks. Emmons, however, believes that the upper marginal part of the batholith is about 5 miles thick; therefore, as the solutions are supposed to have accumulated just beneath it, their source, though in the upper part of the batholith, is what McLaughlin would call "safely out of reach."

Moore in his presidential address last year questioned so close an association between Canadian gold veins and granite cupolas; instead, he emphasized the tendency of the veins and associated dikes of aplite and lamprophyre to lie along the margins of synclines and to be products of the latest stage of differentiation.[38]

[36] Warren, C. H., and Palache, Charles: The pegmatites of the riebeckite-aegirite granite of Quincy, Mass., U. S. A., their structure, minerals, and origin. Amer. Acad. Arts and Sci. Proc. 47: 125–168, 1911.

[37] Butler, B. S., and Vanderwilt, J. W.: The Climax molybdenum deposit of Colorado. Colo. Sci. Soc. Proc. 12: 349–352, 1931; also U. S. Geol. Surv. Bull. 846: 195–237, 1933.

[38] Moore, E. S.: Genetic relations of gold deposits and igneous rocks in the Canadian Shield. ECON. GEOL. 35: 129–139, 1940.

This suggestion rather appeals to me and may serve as a connecting link with the remainder of my comments. If I were acquainted with the geology of Canadian gold veins I might dare to guess whether the same deep zones of weakness that gave rise to granite cupolas also localized later disturbances during which persistent fractures were formed not within the resistant cupola but along its contacts with weaker rocks. Similar structural effects have been produced on a small scale around intrusive masses in the Cripple Creek district, Colo.,[39] and may be permissible on a larger scale in Canada. The occurrence of the Mother Lode, Calif., along a major fault zone [40] encourages one so inclined to think that the gold in the Mother Lode as well as in Cripple Creek and Canada rose from a deep source, perhaps the same one from which the granite had come or even one in the subcrust beneath the granite rather than from the upper part of the granite. Such an inference would place the source still more safely out of reach.

Deposits Associated with Igneous Rocks Intruded During the Long Period of Uplift Following That of Maximum Compression.—Mineral deposits associated with igneous rocks formed during the long period of uplift and fissuring that followed that of maximum compression include ores of many kinds, but consideration will be given to only a few. Those associated with monzonite or granodiorite stocks are of particular interest as they comprise several closely related classes, including contact-metamorphic deposits which are believed by many to have been formed by material given off by the monzonite magma. Different interpretations of the processes involved have been interestingly reviewed by Lindgren.[41] Silicates, metallic oxides, and sulphides, according to some, were deposited at essentially the same time, and according to others, in a rather definite sequence which began with the escape of siliceous material accompanied by little or none of the oxides or sulphides.

[39] Loughlin, G. F., and Koschmann, A. H.: Geology and ore deposits of the Cripple Creek district, Colorado. Colo. Sci. Soc. Proc. 13, no. 6: 331, 333, 372–374, 1935.

[40] Knopf, Adolph: The Mother Lode system of California. U. S. Geol. Surv. Prof. Pap. 157: 9–10, 45–46, 1929.

[41] Lindgren, Waldemar: Mineral Deposits, 4th edit., pp. 696–756, 1933.

The Magdalena district, N. Mex., with which I happen to be acquainted illustrates such a sequence.[42] There, after a long succession of andesite, latite, and rhyolite eruptions followed by a period of pronounced normal faulting, a linear group of monzonitic stocks was intruded along a major fault zone. The structural relations of these stocks in some degree resemble those of stocks along the margin of the great sunken block in the Ouray-Silverton region, Colo. The principal stock, which is the nearest to the largest ore bodies at Magdalena, was intruded along the intersection of the fault zone with a major cross fault. The monzonite is much altered, and close study shows that its marginal facies at least were originally intruded as norite but became converted to monzonitic rock through internal reactions. The latest reaction products in this and the other stocks were of granitic composition, and, at places along contacts between stocks and siliceous wall rock, sandstones and maybe rhyolite also were replaced by granophyre. In short, this stock is somewhat like the norite-granophyre mass at Sudbury, Ont., in the variety of its rock facies. Where emanations from deeper parts of the stocks became depleted of alkalies and alumina while still moving through siliceous rocks, they formed a few large barren quartz veins.

At contacts between the main stock and limestone the high temperature silicates wollastonite, grossularite, and diopside were formed, but were not accompanied by appreciable quantities of metallic minerals. The minerals formed thus far were not related to the particular fault zone along which ore deposition took place later and they may be regarded as having formed by emanations expelled during the crystallization of the stock, especially during the later stages of crystallization.

The dominant constituent of these emanations, as recorded in the minerals that replaced limestone, was silica which formed wollastonite by direct reaction with high-calcium limestone. Any alumina or magnesia, either in the emanations or in the limestone,

[42] Loughlin, G. F., and Koschmann, A. H.: Geology and ore deposits of the Magdalena mining district, New Mexico. U. S. Geol. Surv. Prof. Pap. 200 (in press).

could join with silica and calcium to form grossularite or diopside. The general absence of iron and sulphur is striking. It implies that, if there were any small amounts of these elements in these emanations, either the iron was not in sufficient quantity to form ferruginous silicates and iron oxides or the temperature was too high to permit the formation of these minerals and pyrite within the silicate zone. Where these siliceous emanations, presumably from unexposed stocks, reached limestone after having passed through siliceous wall rock in which they were cooled below the silicate-forming range, they replaced limestone with large masses of jasperoid.

After the stock had become consolidated, fracturing along the main fault zone was renewed and dikes of lamprophyre, now much altered, were intruded into the stocks and adjoining rocks. They were followed by dikes of white rhyolite, which in places became so thoroughly impregnated with pyrite and sericite as to tempt one to regard both minerals as essentially original constituents, although their textural relations are similar to those in rocks where they are clearly of secondary origin. Both kinds of dikes were intruded prior to ore deposition, but the times of their alteration have not been correlated with the period of ore deposition.

A milder renewal of fissuring along the main fault zone gave rise to the deposition of andradite, hedenbergite, and some quartz by the replacement of pure, high-calcium limestone, while adjoining limestone that escaped replacement recrystallized in the form of high-temperature platy calcite. Less pure limestone became replaced to some degree by epidote. These minerals, which are present in certain high-temperature or hypothermal veins in different parts of the world, were not formed at the monzonite contact in the Magdalena district but accumulated in no less than three places along the main fault zone: one near the contact, one half a mile away, and one about 2 miles away. They are believed to represent places where structural conditions, especially the intersection of the main fault zone with certain cross faults, permitted mineralizing solutions to rise from a deep source so rapidly that they could maintain a temperature high enough to permit

the formation of the moderately high-temperature silicates, andradite and hedenbergite, but not such higher-temperature minerals as wollastonite and grossularite.

These centers of mineralization are more clearly related to the fault zone than to the nearest monzonite stock, which had locally obliterated the fault zone and therefore offered greater resistance to renewed disturbance than the repeatedly faulted rocks to either side. Some fracturing in line with the fault zone took place in the monzonite, but there is no evidence of any great invasion of the monzonite by mineralizing solutions at this time. If an appreciable invasion took place, the minerals of the monzonite were evidently not replaceable by such minerals as hedenbergite and andradite. Any other alteration effects that may have been produced in the monzonite at this time are not to be sharply distinguished from those produced earlier or later.

The deposition of andradite and hedenbergite in limestone along the fault zone was closely followed by that of specular hematite and magnetite with some quartz, evidently after temperature had fallen below the stability range of these silicates. No evidence of marked disturbance was recorded between these two stages. The specularite replaced and in part may have grown simultaneously with the platy calcite. It also replaced limestone that had hitherto escaped attack, and was itself coated and partly replaced by magnetite. Small veinlets of these iron oxides and quartz have been noted in the monzonite in line with the fault zone.

Deposition of pyrite followed. Pyrite veinlets distinctly cut masses of specularite and magnetite, though alternate zones of the oxides and pyrite in the marginal parts of some composite crystals indicate that the change from the oxide to the sulphide stage took place in part during a continuous process of deposition. It is interesting to note that the largest mass of essentially pure pyrite found in the district lay against the monzonite contact and extended away from it into the mixture of silicates and oxides—just where it should not be if mineral deposition had been brought about by emanations escaping directly from the crystallizing monzonite.

The pyrite stage was followed by the deposition of iron-rich sphalerite, which replaced any available carbonate within the silicate-oxide and pyritic masses and also formed relatively pure masses in available limestone, some very near the monzonite contact and some far from it. Deposition of galena followed that of zinc blende, partly within the mixed ore already formed and partly in small high-grade streaks.

The position of chalcopyrite in the sequence is not so clear. Chalcopyrite is in part associated with pyrite, though not uniformly, and in part with galena and zinc blende, and it has not been clearly determined whether copper was introduced during all three sulphide stages or only during or just after the galena stage. If introduced late its distribution can be attributed to selective replacement of pyrite or interstitial carbonate in the pyritic masses and to impregnation of zinc blende in the zinc or mixed sulphide shoots, while small amounts were replacing limestone or filling small openings elsewhere.

Where silicates, oxides, and sulphides are so closely associated as to form mixed ore the first impression may be that they were all formed at essentially the same time, but close inspection indicates a definite sequence of deposition. Each successive mineral tended to replace its predecessors to a slight degree, but especially to replace any carbonate that was still available, and to fill any small openings.

With increasing distance from the three centers of deposition the silicates and oxides disappear, quartz and barite with some fluorspar become the principal gangue minerals, and zinc blende contains less iron. The last mineral to be formed in association with the sulphide deposits was the scalenohedral or "dog-tooth" variety of calcite.

The entire history of igneous activity and mineral deposition at Magdalena gives the impression that a residual fluid rich in silica, heavy metals, sulphur, and such volatile or hyperfusible elements as alkalies, hydrogen, oxygen, fluorine, and chlorine accumulated at the roots of intrusive centers while the usual rock-forming materials were being expelled; also that the degree to which they

had accumulated together with the recurrence of fissuring that could tap them determined the sequence of deposition. Where conduits became sealed early in the volcanic history the process came to an early end, as any recurrent disturbance could open or reopen fissures more easily elsewhere. Few of these fissures were deep enough to tap the reservoirs of heavy liquid and at only a few places along them were conduits afforded for the rise of monzonitic material and ore-forming solutions.

If the pyritic rhyolite dikes at Magdalena could be ignored, there would be less tax on the imagination. Iron and other heavy metals could be pictured as accumulating at depth with the ferromagnesian silicates, separating from them by gravitative differentiation, and eventually rising as oxides and sulphides after the heavy silicates had been disposed of in the form of lamprophyre dikes. As remarked earlier, we could even think of gabbros and peridotites with large percentages of pyrrhotite and other sulphides as products of incomplete separation, and by the same reasoning we could think of the lamprophyres, oxides, and sulphides as products of complete separation. The lamprophyres, however, as well as massive oxide and sulphide deposits are accompanied by evidence of hydrothermal action, and we therefore can imagine that the rhyolite dikes represent a liquid well charged with volatile material which remained after consolidation at depth of the material that produced the lamprophyre dikes. In other words, the two kinds of dikes may represent repetition on a small scale of the processes that took place within the monzonite stock, but renewal of fissuring at the right time allowed the residual rhyolite with its high content of volatile constituents to escape instead of reacting with wall rocks near its place of accumulation.

The pyrite and sericite in these rhyolite dikes, even though they have replaced ordinary rock-forming minerals, may correspond to the very last products of the rock-forming process in contrast to those of the distinctly later products of ore deposition, as shown by Burbank [43] in the San Juan region. If they were to be re-

[43] Burbank, W. S.: A source of heat-energy in crystallization of granodioritic magma and some related problems of volcanism. Am. Geophys. Union, Trans. 17th Ann. Meeting, 1936, p. 242.

ferred to the ore-forming stage, their marked preference for the rhyolite dikes would then be even more difficult to explain.

The fluid material that remained below after the intrusion of the rhyolite dikes, or the close of the rock-forming period, was especially rich in iron. The next, still milder, recurrence of fissuring and the consequent release of pressure, as shown by Burbank in the Ouray district,[44] allowed much of this iron to oxidize as it rose along the few available conduits. Temperature at Magdalena, however, was still high enough for the formation of the two calcium-iron silicates, and the ratio of andradite to hedenbergite presumably depended, at least in part, on the ratio of ferric to ferrous iron in the rising fluid. When temperature fell below the stability ranges of these silicates, specular hematite closely followed by magnetite took place.

Owing to the deposition of these iron oxides the ratio of sulphur to the remaining iron was increased and this change, together with subsequent releases of pressure and the continued lowering of temperature, brought about the succession of sulphide stages. The further elimination of iron in pyrite left zinc and later lead and copper as the most available metals to combine with sulphur. Eventually the oxidation of sulphur and the simultaneous release of fluorine and barium through the leaching of rock-forming minerals brought about the deposition of barite and fluorite, and brought the period of ore deposition to a close.

If there were no limit to the length of this address it would be appropriate to review the pertinent features of many other districts and to see to what extent they can be coordinated with the suggestions just presented. Other districts in the West with which I am at least moderately acquainted seem to offer no serious obstacle; otherwise I would be discussing some other subject. It is conceivable that in some districts the latest stages of rock formation could have been followed by the sequence of ore deposition without conspicuous interruption and that certain of the stages so clearly defined at Magdalena might be obscure or unrecognizable.

[44] Idem, pp. 240–249.

At Ajo, Ariz., for example, Gilluly [45] concludes that the main period of sulphide deposition was essentially continuous with the pegmatitic stage that closed the rock-forming period, though the deposition of sulphides was interrupted locally by an interval in which specularite was deposited. In other districts, however, the missing links in the evidence are such that a flexible imagination must come to the rescue. In the eastern and southeastern States, for example, no volcanic rocks or monzonitic stocks similar in structural and time relations to those in Colorado have been reported. We could appeal to prolonged erosion for removal of volcanic rocks but hardly for the absence of monzonite stocks. The only intrusive rocks that are clearly associated with processes of mineralization in that region are Triassic diabases, which occur mainly as sills, for example at Cornwall, Pa., and Goose Creek, Va. It may at first seem far-fetched to regard these intrusions as after-effects of the Appalachian revolution, but the time involved is not incompatible with that covering the orogenic cycle in the East Indian Archipelago; furthermore, when the association of norite with monzonite in the stock at Magdalena, N. Mex., is recalled, the presence of dominant diabasic or gabbroic rocks instead of monzonite in close association with ore deposits is not incompatible. The diabases at Cornwall and French Creek, Pa., are accompanied by magnetite-specularite ores and in this respect are comparable to monzonitic porphyries at Iron Springs and Bull Valley, Utah.

Further speculation to account for the absence of exposed stocks of monzonite in these States would be another interesting indoor sport, but intensive field study with the foregoing pages in mind would be much more to the point. It will suffice here to review briefly certain outstanding features of a few well-known mining districts and to suggest how they may be correlated with the general sequence of processes.

At Ducktown, Tenn., C. S. Ross [46] has demonstrated an unusual

[45] Gilluly, J. A.: Geology and ore deposits of the Ajo district, Arizona. U. S. Geol. Surv. Prof. Pap. (in preparation).

[46] Ross, C. S.: Origin of the copper deposits of the Ducktown type in the Southern Appalachian region. U. S. Geol. Surv. Prof. Pap. 179: 24–31, 40–41, 52–57, 1935.

sequence of mineral deposition, in which an initial aplite-granite stage was followed successively by the deposition of quartz, high-temperature silicates, carbonates, additional silicates, and sulphides. He infers that they are associated with a concealed hypabyssal intrusive mass and that their deposition was a very late episode of the Appalachian revolution. He cites the diabase at Goose Creek, Va., as an example of the ability of differentiating diabase to supply the constituents of high-temperature silicates. He also presents calculations in support of the idea that large amounts of metal and related mineralizing elements may be accumulated through slight deuteric reactions in an average intrusive rock. He concludes [47] " that the most probable source of the sulphide-forming elements seems to have been an immiscible sulphide fraction that remained entrapped in the interstices of the partly crystalline fraction of the parent magma, where it was in immediate contact with the volatile-rich residuum. . . . A sulphide fraction that separated from and sank to the bottom of the silicate fraction—that is, was removed from the environment rich in volatile constituents—seems to be precluded as a source of ore deposits that were formed by volatile-rich solutions."

These processes discussed by Ross accord fairly well with those involved in the proposed general sequence, and reading between the lines by one favorably disposed would doubtless suggest still closer accordance. Further comparison should await the results of detailed areal and structural as well as petrologic and mineralogic study.

The ore deposits of the Cartersville district, Georgia, are closely associated geographically with granitic rocks that are intrusive into folded Paleozoic rocks and appear related to the main compressive period of the Appalachian revolution or its closing stage;[48] but the original gangue minerals of these deposits consist largely of jasperoid and barite,[49] which, together with associated sphal-

[47] Idem, p. 57.

[48] Kesler, T. L.: Geology and ore deposits of the Cartersville district, Ga. U. S. Geol. Surv. report in preparation.

[49] Kesler, T. L.: Sienna ("ocher") deposits of the Cartersville district, Georgia. ECON. GEOL. 34: 333–337, 1939.

——: Structure and ore deposition at Cartersville, Georgia. A. I. M. E. Tech. Pub. 1226: 1–17, 1941.

erite, galena, and pyrite are characteristic of deposits remote from centers of mineralization in such districts as Magdalena. To fit the Cartersville deposits into the picture, therefore, it is necessary to imagine that the monzonitic (or diabasic) intrusion and the higher-temperature stages of mineral deposition took place below the present erosion surface and that the only solutions to reach the surface in noteworthy quantity were of relatively mild temperature.

The zinc-lead deposits of eastern Tennessee and southwest Virginia may be interpreted in the same way as those at Cartersville but, according to the general picture, represent solutions at still lower temperature. They are similar in mineral composition to deposits most remote from centers of mineralization in the outskirts of the Leadville district, Colo., and the Tintic district, Utah.

CONCLUSION.

In the light of this general review of igneous activity and mineral deposition it is impressive to realize what a very small volume is represented by the monzonite stocks in comparison with the volcanic rocks of a region; also the extremely small volume of ore in comparison with any one of the igneous stocks. This small volume of ore together with the sequence of processes and the special structural conditions that controlled its introduction and distribution make it easier to realize why commercial bodies are not found in association with more intrusive centers. It also affords an explanation for the experience that there is a better chance of finding ore by further exploration around well-known centers of mineralization than by hunting for entirely new districts.

The search for new districts is not to be discouraged; in fact, it becomes increasingly necessary as time goes on. A thorough appreciation, therefore, of major structural conditions and their significance, together with the significance of different kinds of rock alteration and mineral deposition, should afford a sound basis for the search. The reasons why many known districts are inadequately mineralized may be more fully appreciated and the

search may be narrowed down to places where these major features offer encouragement.

It is not to be expected that this brief effort to correlate so many different processes into one general sequence is going to meet immediate, unanimous approval, any more than similar efforts by others have. It has helped me toward a more systematic appreciation of the problems pertaining to mineral deposits, and has further convinced me that I have much to learn. Like other general suggestions, however, it is offered as a tentative framework on which to hang facts and ideas. If the geologic facts in many districts fit onto it, problems of exploration in those districts may become clearer; if the facts do not fit, the realization that they do not may lead to other ideas and thereby to the further advance of our knowledge of mineral deposits.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
August 28, 1941.

ARTESIAN WATER IN THE COASTAL AREA OF GEORGIA AND NORTHEASTERN FLORIDA.[1]

V. T. STRINGFIELD, M. A. WARREN, AND H.H. COOPER, JR.

ABSTRACT.

This area is one of the most productive artesian areas in the United States. The wells yield, by flow or pumping, at least 180 million gallons a day, of which six industrial plants use more than 80 million gallons a day; the remainder is used for many different industrial, public, and domestic supplies, or is discharged from flowing wells without being used.

The Eocene Ocala limestone is the principal water-bearing formation, and lies at depths of about 200 to 500 feet. Everywhere within about 25 to 30 miles of the coast, the wells that end in the Ocala limestone will overflow at the surface, except in a few small local areas, and in and near Savannah, where all wells have ceased to flow because of the large withdrawal of water.

The piezometric surface is at present similar to the original piezometric surface except that its coastward slope has been steepened and large cones of depression have developed on it around Savannah and Fernandina by the large withdrawals of water.

Field tests indicate that in the vicinity of Savannah the coefficient of transmissibility of the water-bearing limestone is about 230,000; around Fernandina, Fla., it is less. The shape of the piezometric surface, together with information on the quantity of water taken from wells, indicates that in the vicinity of Brunswick, Ga., and Jacksonville, Fla., the coefficients of transmissibility are much larger than that at Savannah and Fernandina.

The total dissolved solids in Ocala water ranged from less than 175 to about 500 p.p.m.

Although the Ocala limestone contains salt water in the region north and south of the coastal area of Georgia and northeastern Florida, samples of water from the Ocala within the area show no evidence of encroachment of salt water. However, in localities such as Savannah, where large withdrawal of water has formed a large cone in the piezometric surface, encroachment will occur if that cone extends to an area where salt water is present in the formation.

[1] Published with permission of the Director of the Geological Survey, United States Department of Interior. Paper based on results of investigation by Geological Survey, U. S. Department of Interior, in cooperation with Georgia Division of Mines, Mining and Geology and Florida State Geological Survey.

Presented before the Society of Economic Geologists, New York, Feb. 18, 1941.

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INTRODUCTION.

THE area considered in this discussion consists of the six coastal counties of Georgia and two counties in northeastern Florida (Fig. 1). It is one of the most productive artesian areas in the United States and forms a part of the large artesian system of the South Atlantic and Gulf Coastal Plain. In recent years large quantities of artesian water in this area have been developed for industrial use, especially in the manufacturing of pulp for paper. In view of these developments and the possibility that additional large supplies may be needed in the future, investigations are being made by the Geological Survey to determine the quantity of water available.

The investigations are under the direction of Dr. O. E. Meinzer, Geologist in charge of the Division of Ground Water. The work in Georgia is in cooperation with the Georgia Division of Mines, Mining and Geology, and that in Florida is in cooperation with the Florida State Geological Survey. The writers are indebted to Dr. Meinzer and Mr. D. G. Thompson, senior geologist of the Federal Geological Survey, for their helpful suggestions on this work and for reviewing this paper. Acknowledgments are due Mr. Herman Gunter, State Geologist of Florida and Captain Garland Peyton, Director of the Georgia Division of Mines for their effective cooperation and for reviewing this paper. Also

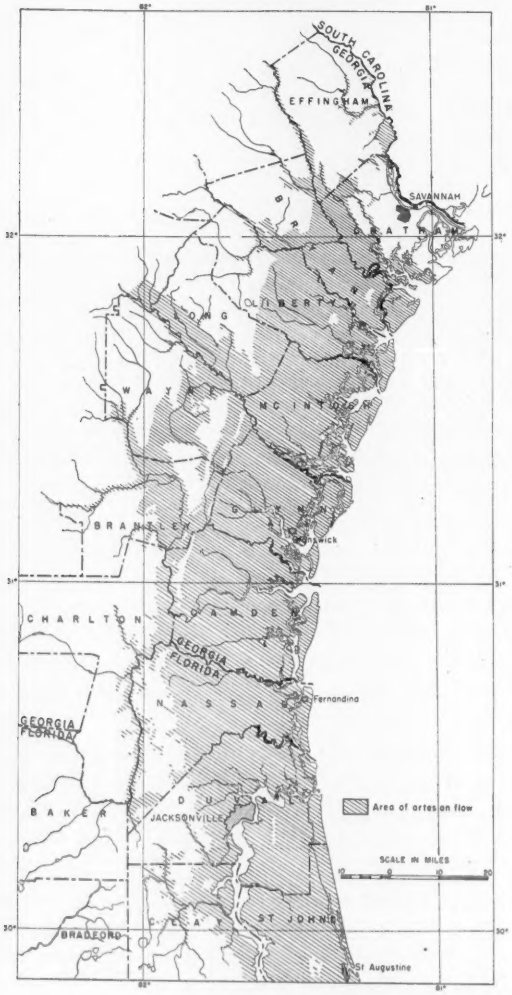

FIG. 1. Area of artesian flow.

acknowledgments are due officials in charge of municipal and industrial plants, owners of wells, and well drillers who have aided the progress of the investigations by supplying data on wells.

The purpose of this paper is to give briefly some of the results of the investigations, including the results of tests and observations made to compute the water-bearing capacity of the principal artesian formation. More complete information is contained in reports now in preparation and in published reports of the State and Federal Surveys.

GEOLOGIC FORMATIONS.

The area is underlain by several thousand feet of sedimentary rocks which range in age from Cretaceous to Recent. The Cretaceous rocks are underlain by an igneous and metamorphic basement that was reached at a depth of 4,355 feet in a well about 2½ miles northeast of Offerman, Georgia.[2] A black shale, which apparently is of Paleozoic age,[3] was penetrated at a depth of 4,635 feet near Hilliard in northeastern Florida.

Cretaceous Formations.—The Cretaceous formations crop out along the inner border of the Coastal Plain and younger formations appear successively toward the coast. In general, the Cretaceous formations dip at low angles toward the south, southeast, or east. These formations are the source of the principal water supplies in some parts of the Coastal Plain, but in the coastal area of Georgia and Florida wells drilled for water do not penetrate the Cretaceous rocks because they are deeply buried and generally contain highly mineralized water.

Eocene and Younger Formations.

The Eocene and younger formations are the source of all of the ground-water supplies in the coastal area. The principal source of artesian water is the Ocala limestone, of Eocene age.

[2] Munyan, A. C.: Oil search in Georgia covers wide front. The Oil and Gas Journal, March 14, 1940.

[3] Campbell, R. B.: Paleozoic under Florida? A. A. P. G. Bull., 23: 1712–1713, 1939.

Campbell, R. B.: Outline of the geological history of Peninsula Florida. Florida Acad. Sci., Proc., 4: 91, 94, 1939.

Ocala Limestone.—The Ocala limestone consists chiefly of several hundred feet of permeable limestone. In the outcrop area northwest of Savannah it grades into the Barnwell sand.[4] The Ocala is underlain by older Eocene limestone and is overlain by the Hawthorn formation, of Miocene age. In part of the area limestone of Oligocene age[5] and limestone tentatively referred[6] to the Tampa limestone, of Miocene age, are reported to be present. The water-bearing properties of these limestones and some of the Eocene limestone which underlie the Ocala are similar to those of the Ocala. Also these rocks have not been differentiated in much of the area under consideration. In view of this, they are regarded as one water-bearing unit as much as 500 feet or more in thickness and are included in the discussion of the Ocala limestone.

The Ocala and associated limestones crop out as an irregular belt north, northwest, and west of the coastal area of Georgia. The Ocala also crops out in north central Florida and is the oldest formation exposed in that State.[7] In the coastal area of Georgia and northeastern Florida the Ocala dips in general toward the coast and ranges from less than 200 feet to about 600 feet below sea level.[8] Along the coast in South Carolina the surface of the Eocene limestone passes below sea level. At Savannah the Ocala is about 200 feet below sea level and about 500 feet below sea level at Brunswick and Jacksonville. South of Jacksonville it rises and is only about 100 feet below sea level at Daytona Beach.

Hawthorn Formation.—The Hawthorn formation, of Miocene age, overlies the Ocala limestone and is present at or near the surface throughout the area. It consists chiefly of limestone, marl, and clay, interbedded with sand, and it ranges in thickness from

[4] Cooke, C. W.: Geology of the coastal plain of South Carolina. U. S. Geol. Surv. Bull. 867: 89, 1936.

[5] Munyan, A. C., op. cit., 1940.

[6] Campbell, R. B., op. cit., p. 91, 1939.

[7] Cooke, C. W., and Mossom, Stuart: Geology of Florida. Florida Geol. Surv. 20th Ann. Rept., 1929.

[8] Mossom, Stuart: A review of the structure and stratigraphy of Florida. Florida Geol. Surv., 1926.

Prettyman, T. M., and Cave, H. S.: Petroleum and natural gas possibilities in Georgia. Georgia Geol. Surv. Bull. 40, 1923.

less than 200 feet to as much as 500 feet. It is overlain by younger formations consisting chiefly of surficial sand and alluvium. The beds of clay and marl in the Hawthorn formation prevent or retard upward percolation of artesian water from the underlying Ocala limestone.

The Hawthorn formation yields both artesian and non-artesian water, but the yield is relatively small as compared with that of the Ocala, and where large supplies are needed water is obtained from the Ocala.

Wells.—After water percolates into the outcrops of the artesian formations and down the dip beneath confining beds of clay and other relatively impervious beds, it is under artesian pressure, which in most of the coastal area is sufficient to raise it to the surface in wells drilled into the artesian formations.

The artesian wells range from about 2 inches to as much as 24 inches in diameter and about 100 feet to as much as 1,250 feet in depth. They are finished without screens and the depths to which they are cased range from about 40 feet to about 530 feet. The yield of the wells by natural flow ranges from a few gallons a minute to about 4,000 gallons a minute.

Area of Artesian Flow.—The area in which wells overflow (Fig. 1), forms a broad belt along the coast except in Chatham County, Georgia, in which Savannah is situated. This belt formerly extended across Chatham County into South Carolina, but heavy withdrawal of water in the Savannah area has caused a decline of artesian head to such an extent that the area of flow now includes only about one third of the county. The area of flow extends up the valleys of the Altamaha, Ogeechee, and Savannah Rivers, almost to the Fall Line.

Piezometric Surface.—The piezometric surface or the height to which water would rise in tightly cased wells ending in the Ocala limestone in 1940 is represented in Fig. 2. A map of the piezometric surface and a discussion of area of recharge and discharge of artesian water in the principal water-bearing formations in the Florida peninsula are included in a report by Stringfield.[9] Also a

[9] Stringfield, V. T.: Artesian water in the Florida peninsula. U. S. Geol. Surv. W. S. P. 773–C, 1936.

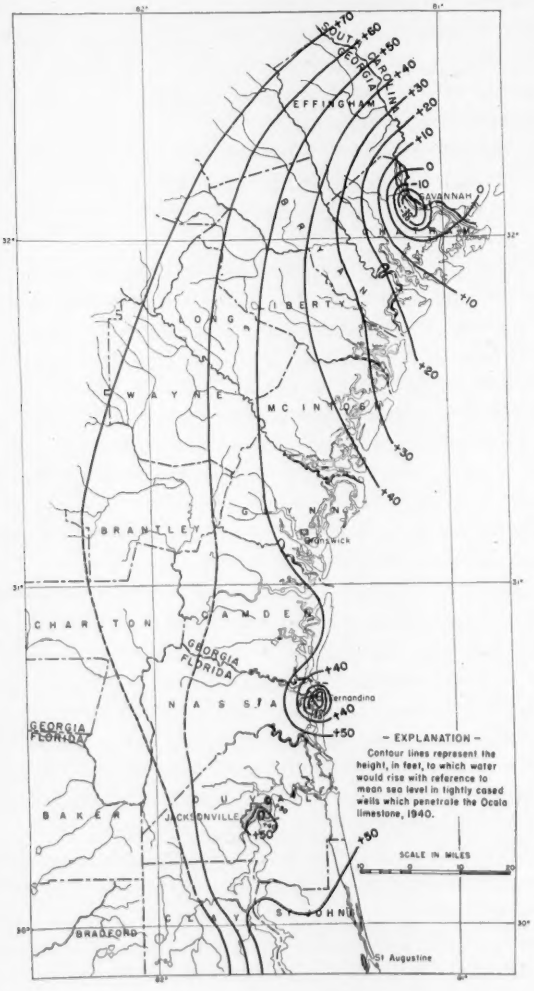

FIG. 2. Map of piezometric surface of artesian water in 1940.

paper by Stringfield includes a generalized map of the piezometric surface in all of the State.[10]

In 1940 the piezometric surface of the artesian water in the Ocala was 70 feet or more above sea level in the western part of the coastal area and about 30 to 55 feet above sea level along the coast, except at Savannah and Fernandina. At Savannah, where the withdrawal of water is about 35 million gallons a day, the piezometric surface is more than 30 feet below sea level and about 70 feet below its original level; and at Fernandina, where the withdrawal is about 33 million gallons a day, the piezometric surface is at or near sea level and as much as 60 feet below its original level. In contrast, at Brunswick, although the withdrawal of water is about 32 million gallons a day, the piezometric surface is about 45 feet above sea level and only about 20 feet below its original level; and at Jacksonville, where the withdrawal of water is about 35 million gallons a day, the piezometric surface is about 30 feet above sea level and only about 30 feet below the original piezometric surface. Since the Ocala limestone yields water to the wells at each of these localities and the geologic conditions are similar, the differences in the shape and elevation of the piezometric surface indicate significant differences in the water-bearing capacity of the Ocala limestone.

The present piezometric surface appears to be similar to the original piezometric surface (Fig. 3) except that its coastward slope has been steepened and large cones of depression have been developed in areas where large quantities of artesian water are being withdrawn. Prior to the development of the large cone at Savannah the artesian water converged toward that area from the southwest, west, and northwest, indicating a discharge area offshore northeast and east of Savannah.

Water-bearing Capacity of the Ocala Limestone.—The Ocala limestone is noted for its large yield to wells and springs. It is the source of some of the largest limestone springs in the United

[10] Stringfield, V. T.: Ground-water supplies in Florida (an abstract), Civil Engineering, 8: 457–458, 1938.

Stringfield, V. T.: Ground-water in the Southeastern States. Southeastern Sect. Am. Water Works Assoc. 9: 58–70, 1940.

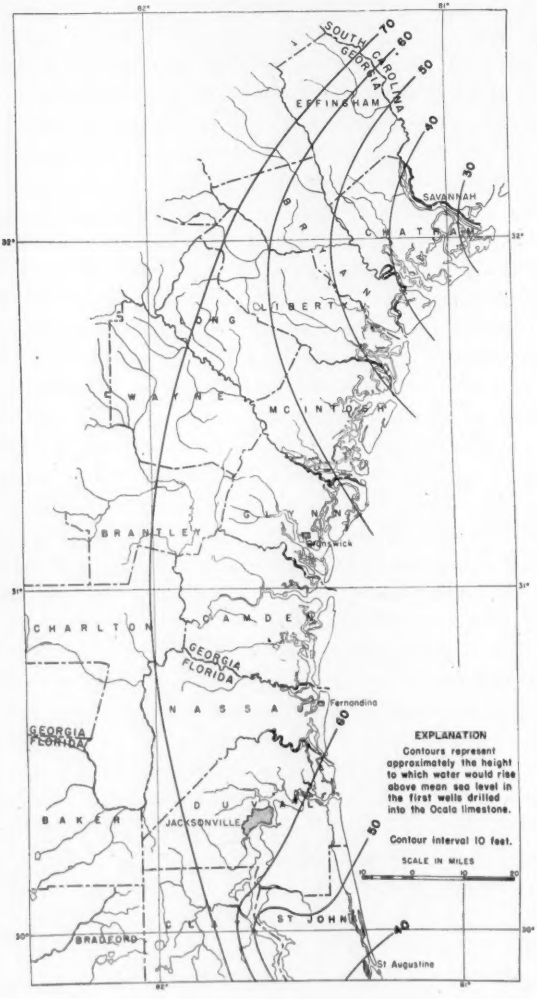

FIG. 3. Map of original piezometric surface of artesian water.

States, the largest of which is Silver Springs, near Ocala, Florida, the flow of which has ranged from about 340 million to 800 million gallons a day.[11]

Tests on wells in the vicinity of Savannah indicate that the coefficient of transmissibility [12] of the Ocala limestone is about 230,000—that is, for each mile of width of the formation about 230,000 gallons of water a day percolates through the formation for each foot per mile of hydraulic gradient. With a thickness of 400 feet of permeable limestone and a temperature of 72° F., the coefficient of permeability as defined by O. E. Meinzer in a report by Stearns [13] is computed to be about 500.

Tests on wells in the vicinity of Fernandina indicate that the coefficient of transmissibility is somewhat less than at Savannah. No similar tests have been made in the vicinities of Brunswick and Jacksonville but the shape of the piezometric surface together with the quantity of water taken from wells, show the coefficients of transmissibility are much larger in these two localities than at Savannah and Fernandina. Although the withdrawal of water from wells is approximately the same at Brunswick as at Savannah, there is no appreciable depression of the piezometric surface at Brunswick, whereas there is a pronounced cone of depression at Savannah (Figs. 2, 4).

Consumption of Water.—All of the public water supplies in this area, including those of Savannah and Jacksonville, are obtained from wells. The Jacksonville supply is probably unique in being the largest public supply in the United States obtained entirely by natural flow from artesian wells.

It is estimated that the artesian wells in the area yield, by natural flow and pumping, at least 180 million gallons a day. Of this amount, six industrial plants use more than 80 million gallons a day; the remainder is used for industrial, public, and domestic

[11] Stringfield, V. T.: Artesian water in the Florida peninsula. U. S. Geol. Surv. W. S. P. 773–C: 155, 1936.

[12] Theis, C. V.: The relation between the covering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. Am. Geophys. Union, Trans.: 1935, pp. 519–524.

[13] Stearns, N. C.: Laboratory test on physical properties of water-bearing materials. U. S. Geol. Surv. W. S. P. 596: 148, 1927.

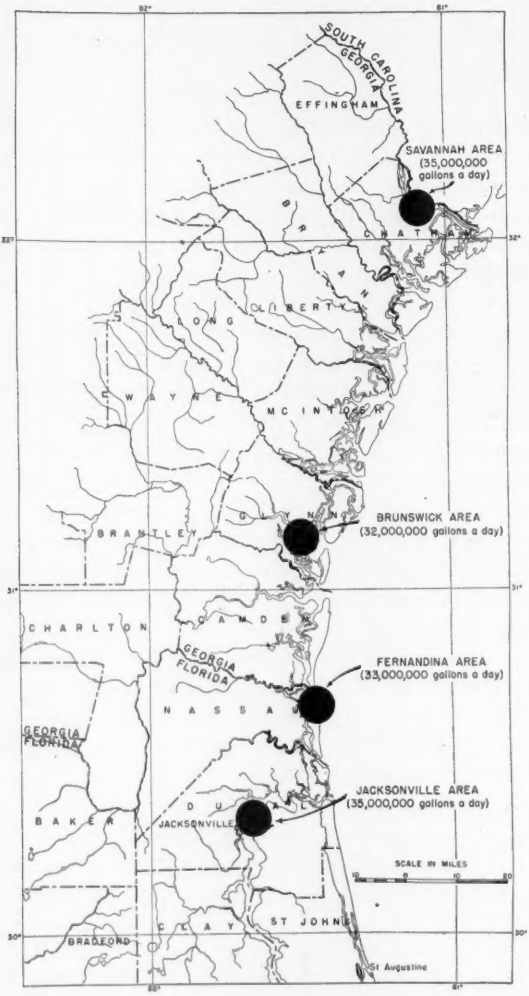

FIG. 4. Consumption of artesian water in the principal industrial areas.

supplies, or is discharged from flowing wells without being used. All of this water is obtained from the Ocala limestone except some of the domestic supplies are from the Hawthorn formation. The consumption of water in four areas where the largest supplies have been developed all of which are from the Ocala limestone is shown in Fig. 4.

Quality of Water. Results of chemical analyses of water in this area are contained in several reports.[14]

These records together with unpublished analyses indicate that the total dissolved solids in samples of water from wells that yield water from the Ocala limestone ranged from about 175 to about 500 parts per million. The range in hardness was from about 100 to about 350 parts per million. Hydrogen sulphide is also present in much of the Ocala water, especially in the southern part of the area.

The total dissolved solids and hardness of the water are higher in the southern part of the area due largely to the presence of calcium sulphate.

Salt Water Encroachment.—In coastal areas the problem of salt water contamination of fresh ground water is an important factor in a study of the safe yield of the water-bearing formations. The general relations between fresh water and salt water along sea coasts were first determined through the work of European investigators.[15] These studies showed that in the coastal areas investigated, the depth to salt water is largely a function of the height of the water table above sea level and the difference in the specific gravity of the fresh water and the salt water. This relation is expressed by the simple formula: $h = \frac{t}{g-1}$, in which h is

[14] Collins, W. D., and Howard, C. S.: Chemical characters of Florida waters. U. S. Geol. Surv., W. S. P. 596G, 1938.

McCallie, S. W.: Underground waters of Georgia. Georgia Geol. Surv. Bull. 15, 1908.

Stephenson, L. W., and Veatch, J. O.: Underground waters of the Coastal plain of Georgia. U. S. Geol. Surv., W. S. P. 341, 1915.

[15] Brown, J. S.: A study of coastal ground water with special reference to Connecticut. U. S. Geol. Surv. W. S. P. 537, 1925.

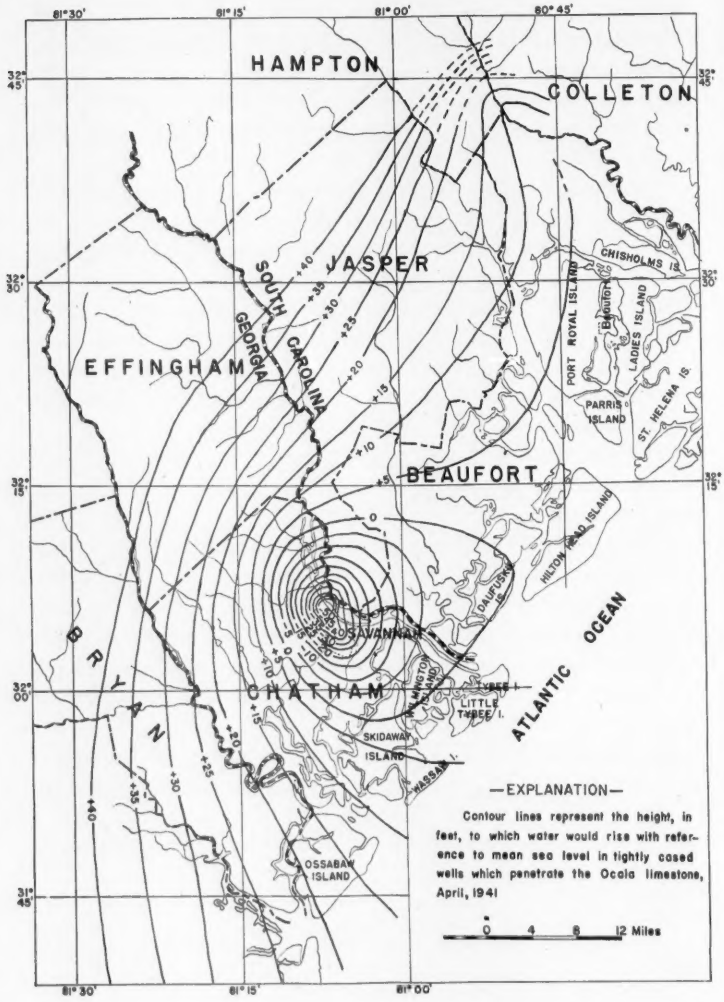

FIG. 5. Map of piezometric surface of artesian water in Savannah and adjacent areas in 1941.

the depth of the fresh water below sea level, t is the height of the fresh water surface above sea level, and g is the specific gravity of the salt water. The specific gravity of sea water differs somewhat from one locality to another and may also be different at different depths. If the specific gravity of the sea water is about 1.025 and the water table or hydrostatic head is 10 feet above sea level, the depth to the contact between salt and fresh water is according to the formula, about 400 feet below sea level. In other words, for each foot of fresh water head above sea level, the fresh water extends 40 feet below sea level. In regions such as the coastal area of Georgia and northeastern Florida, the artesian formations are overlain and underlain by relatively impervious beds and the water is under artesian pressure, but the same general principle applies. The relative impervious beds prevent the underlying salt water from reaching the wells but lateral encroachment from contaminated areas or submarine outcrops will occur if the artesian pressure is insufficient to prevent it. The lateral movement of the artesian water may be only a few feet each year and of course lateral movement of the salty ground water will be slow. Under these conditions wells at some distance from contaminated areas may yield fresh water for some time even though the cone of depression has extended to the contaminated areas.

Although the Ocala limestone contains salt water in the region north and south of the coastal area of Georgia and northeastern Florida, samples of water from the Ocala within the area show no evidence of encroachment of salt water. However, in localities, such as Savannah (Fig. 5), where large withdrawal of water has formed a large cone in the piezometric surface, encroachment will occur if that cone extends to an area where salt water is present in the formation. Also wells drilled through the relatively impervious beds that underlie the fresh water-bearing formation contaminated with salt water, and wells with defective casings where the Hawthorn formation or other surficial formations contain salt water may become contaminated.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
June 18, 1941.

TITANIFEROUS MAGNETITE DEPOSITS OF SEPT-ILES, QUEBEC.

CARL FAESSLER AND G. M. SCHWARTZ.

ABSTRACT.

Titaniferous magnetite rocks crop out along streams that enter the St. Lawrence river in the Sept-Iles area. The deposits, found in a gabbro and anorthosite complex, are somewhat similar to other titaniferous deposits in Quebec and elsewhere.

The microtexture shown by the magnetite-ilmenite intergrowths is of a novel type—an en échelon arrangement of the ilmenite lamellae in the magnetite. The abnormal arrangement of the lamellae is inferred to be a result of a distortion of the magnetite between the time of crystallization and the time when the temperature of ex-solution was attained.

FOREWORD.

DURING the preparation of a suite of polished ores for the economic geology laboratory of Laval University a specimen from the Sept-Iles area was polished for the purpose of illustrating the relations of ilmenite and magnetite in titaniferous iron ores. Instead of the usual ilmenite inclusions arranged along the octahedral planes of the magnetite, a rather irregular arrangement of ilmenite in magnetite was found. Preparation of additional polished surfaces of available specimens showed that the ore is characterized by an unusual magnetite-ilmenite texture that does not appear to have been described from any other region. Detailed studies suggest a possible explanation for the unusual intergrowth.

The deposits of magnetite at Sept-Iles bay, and the magnetite sands to the east near the mouth of the Moisie river, 16 miles beyond Sept-Iles, were observed by the early settlers. Smelting works to utilize the sands were erected in 1867, at the north of Moisie river, and are reported to have remained in operation for a few years, but the plant was dismantled in 1875.

The Molson Mine (really a quarry) was opened at the time the furnace was built to utilize the Moisie sands. A small amount of

the Molson Mine ore was used in the furnace but, probably on account of the high titanium content, nothing came of the venture.

The writers are indebted to Mr. A. O. Dufresne, Director of the Quebec Bureau of Mines, for permission to publish the field data on which part of the paper is based. Dr. J. D. H. Donnay made several suggestions and kindly read the manuscript. The laboratory work was done in the research laboratories of Laval University, Quebec.

PREVIOUS WORK.

The deposits of Sept-Iles bay were mentioned by Sterry Hunt [1] in 1869 and later by Ells [2] and Obalski.[3] A much more detailed report was published by Dulieux [4] in 1915, and the writers have drawn freely on this work for data not covered in later field work in the area. Dulieux examined the deposits in considerable detail and described the geology in the immediate vicinity. Several analyses of the ores are given in the report and estimates were made of the probable amount of titaniferous iron ore available.

Map and reports on the geology of the North Shore of the St. Lawrence river, from the Godbout river to Sept-Iles and from there to Matamec river, have been prepared by Faessler and will be published by the Quebec Bureau of Mines.

LOCATION AND PHYSIOGRAPHIC SETTING.

The Sept-Iles area is situated on the northern shore of the St. Lawrence river, approximately 300 miles north-east of Quebec City. It is crossed by longitude 66° 30′ and latitude 50° 15′.

The seven islands (actually six islands and a peninsula) are conspicuous landmarks and their highest elevations vary from 260 to

[1] Hunt, S.: Canada Geol. Surv. Report of Progress from 1866 to 1869 (French edition), p. 288.

[2] Ells, R. W.: On the mineral resources of the Province of Quebec. Geological and Natural History Survey of Canada, Ann. Rept., 4: 14 K, 1888–89.

[3] Obalski, M. J.: Mines et minéraux de Québec, Québec, 14, 1889. Dept. des Terres, Mines et Pêcheries, Opérations minières dans la Province de Québec, 10–11, 1901.

[4] Dulieux, P. E.: Les minerais de fer de la Province de Québec, Ministère de la Colonisation, des Mines et des Pêcheries, 1915.

738 feet above sea level. The river at this point is 70 miles wide and the Laurentian highland rises in the rear of Sept-Iles bay, which is cut deeply into the sandy terrace of Champlain age. These terraces form the poorly drained plains that skirt the St. Lawrence in this area for a long distance. The islands and the peninsula of the archipelago are the only rocky outcrops along the shore, except at the mouth of the Des Rapides river where the bay reaches the foot of the Laurentian highland. At Sept-Iles the lowland, floored with Champlain deposits, is limited to about five miles in width. The highest terrace of the post-glacial Champlain sea is 420 feet above sea level so that the sediments are not confined to the plains, but extend into the higher areas, especially along the river valleys, and cover the pre-Cambrian bed rock at many places.

The Laurentian plateau, outside of the region here described, in most places extends to the St. Lawrence; in the Sept-Iles area, however, plateau level is reached only at a distance of 4 to 6 miles inland. The general plateau elevation varies from 900 to 1300 feet above sea level.

GEOLOGY OF THE AREA.

General Statement.—Sept-Iles bay is an almost circular wave-cut hole in a sand plain of Champlain age underlain by glacial boulder clay. At its outer margin, a rim of coarse boulders shows at low tide. Above the Champlain deposits, low rocky ridges, forming part of the Laurentian shield and covered mostly with a thin layer of morainic material, rise to a maximum elevation of 1350 feet. These rocks outcrop also at the bottom of the river valleys that are cut deeply into the Champlain sediments, for example the lower portions of Marguerite and Des Rapides rivers. All the consolidated rocks are of pre-Cambrian age and belong almost exclusively to the Granite Gneiss series and the Morin series, both igneous, the latter intruding the former. The iron ore deposits described in this paper are found exclusively in close relation with the Morin series. Some still younger intrusives, of the diabase-gabbro type, cover a small portion of the area described.

Granite Gneiss.—The oldest rocks in the area represent what is generally called "Laurentian Gneiss." A red color, highly gneissic texture, and granitic composition characterize it. Biotite is its most abundant mafic constituent and orthoclase its most abundant feldspar. In the rocks of the area here described, augen structure has not been observed, whereas it is common in the gneisses of adjoining areas. It is rather doubtful that the gneisses mapped in the Des Rapides river area really belong to the Granite Gneiss series. In fact the study of the contact zone suggests that some of the gneisses are younger than the basic rocks of the Morin series. Some gneisses may, therefore, be acidic phases of the Morin series. No good contacts between the Morin series and undoubted "Laurentian" gneisses are seen in the area. There always seems to be a continuous transition between the two.

Morin Intrusives.—The iron ore deposits are found in rocks of the Morin series. Anorthosites and associated rocks, grouped together in the Morin series (Buckingham series of some authors), cover some restricted and widely separated areas along the North Shore of the St. Lawrence river.[5] Older maps show some of these masses connected with the huge anorthosite body known to exist in the Lake St. John area, 120 miles north of Quebec City, but it is now known[6] that the anorthosite bodies of the North Shore are isolated masses, surrounded by older granitic gneisses or metasedimentary rocks.

One of these masses is the Sept-Iles anorthosite body. It covers about 60 square miles, mostly concealed under a thick layer of Quaternary sediments and the water of Sept-Iles bay. Rocks of the Morin series outcrop in the bed of the Marguerite river, near the town of Clarke City, and along the Des Rapides river; they emerge from the Champlain plain north-west of Sept-Iles bay, forming a rocky plateau several hundred feet high at the edge of the Laurentian highland. The six rocky islands at the entrance

[5] Faessler, C.: Geological exploration on the North Shore, Manicouagan to Godbout, Quebec. Bur. Mines, Ann. Rept. 1933, Part D, 149–165, map No. 302, Franquelin sheet, 1933.

[6] Faessler, C.: Geological exploration on the North Shore, Godbout to Sept-Iles, Quebec. Bur. Mines, Geol. Rept. in press, map No. 503, Sept-Iles sheet, 1940.

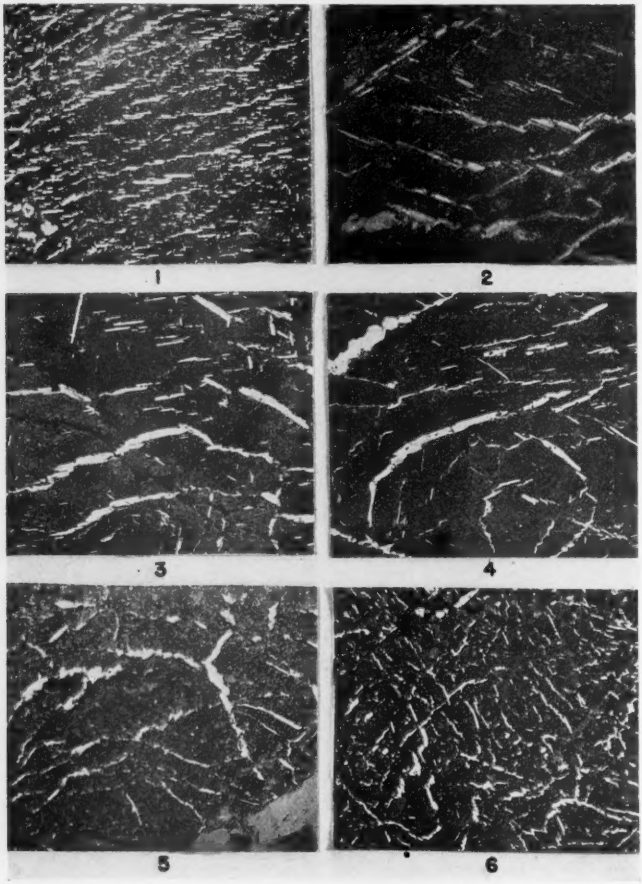

FIG. 1. Diagrammatic en échelon arrangement of ilmenite in magnetite (etched). Contact of microgabbro and ore. Molson Mine. ×90.

FIG. 2. Typical en échelon arrangement of ilmenite (etched). Some grains are irregular. Molson Mine. ×90.

FIG. 3. Somewhat curved zones of en échelon ilmenite lamellæ in magnetite (etched). Molson Mine. ×70.

of the bay are part of this anorthosite body, as well as the "seventh island."

The Morin series, in this area, comprises a great variety of rocks. In the interior plateau, the most abundant rock is an iron-rich gabbro. In the archipelago, anorthosite and gabbro alternate with more acidic rocks, in broad bands showing sharp contacts. Along these contacts, a brecciated zone is usually observed, showing the acidic rock to be younger than the basic rock.

Basic Facies.—Coarse anorthosite is abundant in this area and especially in the archipelago. Plagioclase crystals may exceed two feet in length. Stout crystals of hypersthene, from several inches to two feet across, commonly accompany the plagioclase. Brecciated anorthosite embedded in an anorthositic or gabbroic matrix, is very common, especially along the eastern shores of the peninsula. In the Des Rapides river area, and at many nearby places outside of the area described here, the gabbro contains round lumps of a whitish anorthosite. These lumps must belong to an older plutonic intrusion and have been brought up in a solid state by the younger gabbro.

A peculiar feature of the basic facies in this area is the presence of what may be called "books" of plagioclase twin-crystals. The crystals are grouped together in a parallel arrangement (Fig. 11) so that a transverse section gives the impression of the edge of a book. Such a "book" may be several feet across.

In the Des Rapides river area the predominant rock is a very dark colored, iron-rich gabbro. It may exhibit a somewhat banded structure—iron-rich bands alternating with iron-poorer bands. These bands grade into one another. With an increase of the iron content such bands may become ore-bodies.

Acidic Facies.—No acidic rocks have been encountered near the

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FIG. 4. Irregular curved inclusions of ilmenite in magnetite (etched). Molson Mine. × 240.

FIG. 5. Irregular stringers and isolated lamellæ of ilmenite in magnetite (etched). Molson Mine. × 90.

FIG. 6. Fine-grained ilmenite inclusions in magnetite. Many inclusions are irregular in shape and distribution (etched). Molson Mine. × 90.

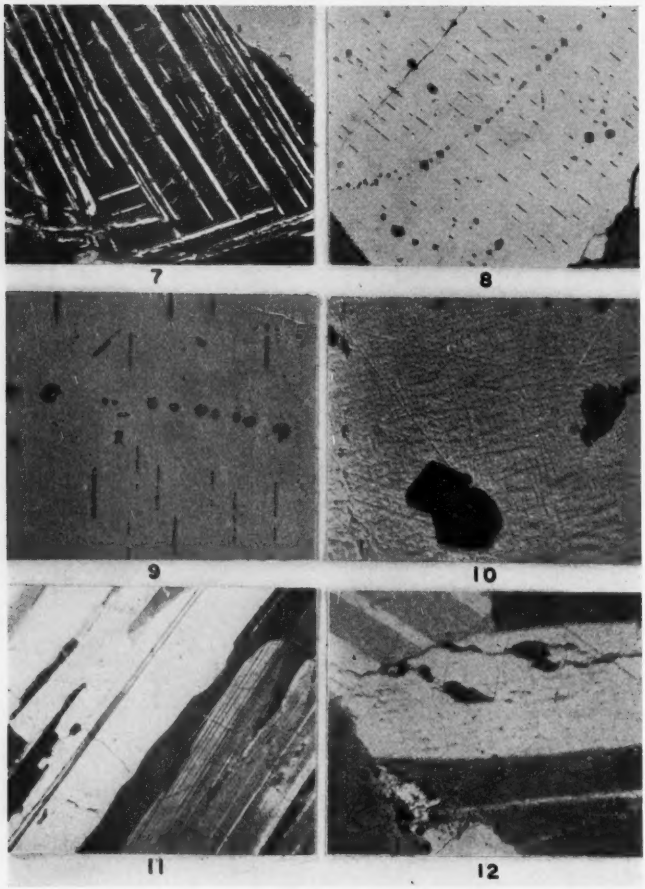

FIG. 7. Regular inclusions of ilmenite in a magnetite grain in gabbro. Chute à l'Outarde. Des Rapides river. × 90.

FIG. 8. Spinel inclusions in magnetite (unetched). Molson Mine. × 90.

FIG. 9. Higher magnification of same specimen as Fig. 8. Spinel as subhedral crystals and lamellæ in magnetite. Molson Mine. × 250.

ore deposits, but they are abundant in the archipelago. All the islands consist of alternating basic and acidic masses, with a brecciated contact zone, several feet wide, composed of angular blocks of basic rock (anorthosite or gabbro) in an acidic matrix. These well marked contact zones are a striking feature of the islands. Elsewhere, along the North Shore of the St. Lawrence as well as in other anorthosite bodies of the continent, the acidic and the basic facies commonly grade into each other.

PETROGRAPHY.

Basic Facies.—Most of the anorthosites in this area are dark, coarse-grained rocks, known locally as "black marble." Under the microscope they show fresh crystals of calcic plagioclase (An_{60} to An_{80}), twinned in broad lamellae (Fig. 12). They generally do not exhibit granulation and, except for an occasional wavy extinction, do not show any sign of crushing or shearing. Other minerals present are hypersthene, and rare biotite and hornblende; olivine is absent. With an increase in mafic minerals, anorthosites grade into gabbros. Iron-rich gabbros of the Des Rapides river district may contain as much as 20 per cent iron ore (as magnetite and ilmenite).

The inclusions of white anorthosite are quite different from the enclosing dark anorthosite. The plagioclase is highly altered and most of it has been converted to an intricate mixture of carbonate, clinozoisite, epidote, and sericite. The plagioclase of the "books" described above, has a dusty appearance, shows some alteration to calcite and sericite, but does not exhibit granulation. Some highly altered hypersthene and biotite appear alongside the plagioclase crystals.

Acidic Facies.—The syenites and granites, undoubtedly related

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FIG. 10. Spinel twin (?) included in an intergrowth of magnetite and ilmenite. Molson Mine. × 900.

FIG. 11. Photograph of a thin-section of anorthosite showing parallel arrangement of twinned crystals of plagioclase. × 18.

FIG. 12. Basic plagioclase in very coarse-grained ordinary anorthosite. × 18.

to the Morin series, are characterized by an abundance and variety of feldspars. Generally perthite predominates, along with orthoclase and some plagioclase. Quartz, if present, generally exhibits a bluish tint. Common mafic minerals are hornblende and titanite. Accessory minerals are biotite, augite, hypersthene, and apatite.

TITANIFEROUS MAGNETITE DEPOSITS.

Distribution.—There are two groups of titaniferous magnetite deposits in the area described: the Marguerite and the Des Rapides river groups. The two are separated by a distance of about 10 miles, occupied mainly by a plain of Champlain sands. Both were examined by Faessler in 1938 and in 1939. A detailed study of them had been previously made by Dulieux.[7]

The Marguerite river empties into the St. Lawrence 4 miles west of Sept-Iles bay where a small village of the same name is located on the western bank. Four miles above its mouth is the village of Clarke City, built on sand banks about 100 feet above water level.

There are two deposits of titaniferous magnetite along the shores of the Marguerite river, near Clarke City. The first one is situated at the foot of the first fall, outcroping at the water edge on the east side of the river. The country rock is a dark anorthosite containing some hypersthene. It grades into an iron-rich gabbro, which in places is so much enriched in titaniferous magnetite that it becomes an ore deposit with some 70 per cent FeO and 20 per cent TiO_2. The rich ore, however, occurs in small, disconnected, lens-shaped, masses, grading into an iron-rich gabbro; the largest is about 15 by 80 feet. Dulieux estimates the quantity of good ore available there at only about 10,000 tons.

Still less important is the second deposit, located on the same side of the river, a short distance above Clarke City. Some ore is also visible on the right bank of the river, across from the first deposit.

The Des Rapides river empties into Sept-Iles bay, and the deposits, consisting of two distinct, separated, ore-bodies, are located

[7] Op. cit.

on the rocky shores of the river, between its mouth and the Des Rapides lake, 5 miles upstream. They are the Molson Mine and the Outarde Fall deposit.

The Molson deposit is located at the foot of the second fall of the Des Rapides river, ¾ mile from its mouth; it is of the same

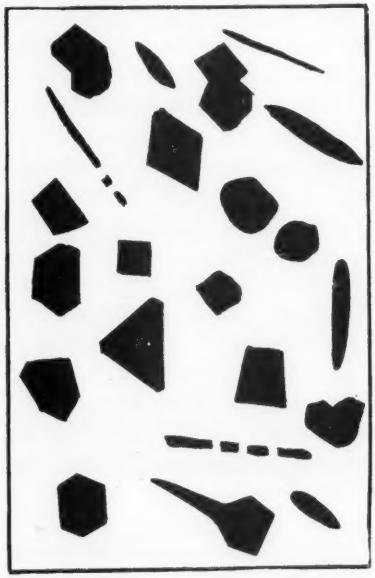

FIG. 13. Sketch of the shape of various grains of spinel included in magnetite. ×700.

type as the Marguerite river deposit. The ore outcrops on both sides of the river, along the vertical cliffs forming the walls of the river bed. The country rock is a black, fine-grained gabbro, which in places includes large rounded lumps of whitish anorthosite. There is a continuous gradation from gabbro to ore, but sharp contacts are observed between the ore and the inclusions of white anorthosite. Dulieux estimates the proven quantity of good ore at some 300,000 tons. This ore would average 50 to 52 per cent

iron and 12 to 15 per cent titanium. Obalski gives a rough estimate of several million tons of ore.

The Outarde Fall deposit is located 1½ miles higher up the river, at the foot of Outarde Fall (Goose Fall).[8] This deposit, located along both banks of the river, consists of an iron-rich gabbro with very little ore. This gabbro contains 25 per cent iron and 10 per cent titanium, according to analyses given by Dulieux. It forms the cliffs along the Des Rapides river for a distance of some 300 feet, and grades into an ordinary gabbro. This iron-rich gabbro is often encountered in the adjoining area.

Structure and Origin.—The titaniferous magnetite deposits of the Sept-Iles area, like similar deposits elsewhere in Quebec, occur as irregular masses, preferably along the outer zones of the anorthosite-gabbro body. In places they are thinly banded, the individual bands rarely exceeding two feet in thickness (15 feet at the Marguerite river). The bands have a maximum length of 80 feet, and pinch out at both ends. The contact between the iron-rich gabbro and the ore lenses is everywhere gradational. The writers' conclusion is that these ore-bodies are due to magmatic segregation from an iron-rich magma. Other authors have attributed a hydrothermal origin to similar ore-bodies,[9] but no evidence in favor of such a hypothesis has been found in the area here described.

MICROTEXTURES OF THE TITANIFEROUS MAGNETITES.

Magnetite-Ilmenite.—The titaniferous magnetite occurs in masses that vary from nearly pure ore minerals to gabbro with a normal amount of magnetite and ilmenite. The gabbro generally is richer in ilmenite than in titano-magnetite.

Thirty polished surfaces of ore and associated rocks were studied. A laboratory sample of several hundred pounds of ore from the Molson Mine was available, and several of the surfaces

[8] A nearby lake, called "Outarde Lake" by Dulieux, is known to the people of Sept-Iles as Duck Lake (lac Canard).

[9] Gillson, Joseph L.: Genesis of the ilmenite deposits of St. Urbain, county Charlevoix, Quebec. ECON. GEOL., 27: 554–577, 1932.

were prepared from this material as well as from other samples of ore collected from the mine by C. Faessler.

In all specimens ilmenite occurs abundantly as anhedral grains, intergrown with similar grains of titano-magnetite. In most specimens the ilmenite grains appear to be about as abundant as the titano-magnetite grains, but in some the ratio is 2 to 1 in favor of magnetite. Calculations based on an analysis of ore given by Dulieux [10] indicate a ratio of ilmenite to magnetite of about 55 to 45. The mutual relationships of the grains are similar to those described by Singewald [11] for the titaniferous magnetite deposits of the United States.

The usual intergrowths of ilmenite lamellae along the octahedral planes of magnetite are familiar to every student of polished sections of ores. In the massive titaniferous magnetites of the Sept-Iles deposits, however, the simple octahedral arrangement of the lamellæ is the exception rather than the rule. The intergrowth is also unlike the arrangement in twinned magnetite which has been described by several investigators.[12] In general it was found that magnetite in the gabbro of the Sept-Iles region, unlike that in the ore, shows the normal octahedral intergrowth of ilmenite lamellæ (Fig. 7). The more massive ore shows a much more irregular arrangement, varying from a rather diagrammatic en échelon type to almost complete irregularity. Variations in the appearance of this abnormal type are illustrated in Figs. 2 to 6. By far the most common arrangement is a series of blades forming en échelon zones across the magnetite (Figs. 1, 2). Less commonly the ilmenite forms somewhat curved stringers (Fig. 3). These may be composed in part of en échelons lamellæ or simply-curved or irregular stringers (Fig. 4). The contrast of the abnormal textures with the normal type may be readily seen by comparing Figs. 1 to 6 with Fig. 7 or by comparing the photo-

[10] Op. cit., p. 67.

[11] Singewald, J. T., Jr.: The titaniferous iron ores in the United States, U. S. Bur. Mines, Bull. 64: 30–31, 1913.

[12] Donnay, J. D. H.: Genesis of the Engels copper deposit. Congrès international des Mines, de la Métall. et de la Géologie appliquée, VIe session, Liège 1930. Section de géol., 99–111.

graphs accompanying this paper with those published by Singewald [13] and others.[14] It should be noted that the irregularity of the Sept-Iles specimens is most evident at low magnifications (50 diameters or less), but for photography it was found desirable to use somewhat higher magnifications.

Polarized reflected light is useful in studying the inclusions, but etching is better because grains of all orientations may be seen at one time. In polarized light it is evident that most inclusions of ilmenite in a given magnetite grain have a common optical orientation as they extinguish in unison. It is also clear that there is a preferred direction for the inclusions as they are generally abundant in one series of parallel planes and rather scarce in other directions. Commonly only one other plane direction seems favored by ilmenite. In some of the specimens that show the en échelons and irregular inclusions of ilmenite, segregation to grain boundaries of the magnetite was observed. In many cases stringers cut across the grains and some of these show a narrow zone of lattice-work of ilmenite on each side. The grains in the stringers usually show a random orientation but the ilmenite lamellæ of the lattice-work are arranged along octahedral planes and could reasonably be interpreted as of later origin than the abundant en échelons and irregular inclusions. At places these cross-cutting stringers might even be called veinlets.

In a few polished surfaces both the normal octahedral intergrowth and the irregular abnormal type occur together but always in separate areas, sharply differentiated from one another. One specimen shows a vein of magnetite crossing magnetite gabbro. The vein consists of coarse grains of ilmenite and magnetite, and intergrowths of both types occur in the magnetite of the vein.

Ilmenite, in some of the specimens, shows parallel intergrowths of magnetite as long continuous blades, and also as the dashed-line type.

[13] Op. cit.

[14] Warren, C. H.: On the microtextures of certain titanic iron ores. ECON. GEOL., 13: 419–446, 1918. Schwartz, G. M.: The relations of magnetite and ilmenite in the magnetite deposits of the Duluth gabbro. Am. Mineral., 15: 243–252, 1930.

Examination at magnifications up to 1,000 diameters reveals no visible texture, within the magnetite grains, that might account for the abnormal character of the intergrowth. There seems to be no direct evidence that the en échelon arrangement is a result of displacement of the ilmenite lamellae after they had ex-solved from the magnetite. In fact careful study of the arrangement of the lamellæ in many specimens, leads to the conclusion that no conceivable later movement could give the observed spacing of lamellæ. That ilmenite inclusions in magnetite are an unmixing product has been rather universally accepted. Ramdohr's [15] experimental work provides a basis for this conclusion. As may be observed in the photographs, there is no evidence of shearing or fracturing where the ilmenite laths are offset or curved. This is true of all the polished surfaces examined. It seems, therefore, that the cause of the unusual arrangement of the ilmenite lamellæ must antedate the unmixing.

The deposits of the Sept-Iles area are of limited extent, and most of the specimens came from the pit of the Molson Mine or nearby outcrops on the Des Rapides river. However, a specimen from exposures on the Marguerite river, 10 miles to the west, shows similar textures. This suggests that the origin of the abnormal texture is related to conditions prevailing in the intrusive as a whole, rather than to some local cause in the vicinity of the Des Rapides river. It was found, as previously noted, that the irregular arrangement of the ilmenite lamellæ occurs only in the more massive ore specimens. Specimens of gabbro, magnetite gabbro, and anorthosite show the usual regular arrangement (Fig. 7).

Titaniferous magnetites from several other areas in the Province of Quebec were also examined, but of the available specimens only those from the Sept-Iles area are abnormal.

Sulphides are fairly common in the polished specimens, but only pyrite, pyrrhotite, and chalcopyrite were noted.

[15] Ramdohr, Paul: Beobachtungen an Magnetit, Ilmenit, Eisenglanz und Ueberlegungen ueber das System, FeO, Fe_2O_3, TiO_2. Neues Jahrbuch fuer Mineralogie. Beilageband LIV. Abt. A, 320–379, 1926.

Magnetite-Spinel.—A few polished specimens contain transparent inclusions in regular arrangement. They come from outcrops on the Des Rapides and Marguerite rivers. They were studied in some detail, but attempts to isolate the minute inclusions for identification have failed. The available data, however, seem to eliminate all minerals other than spinel. Examination at magnifications up to 1,000 diameters indicates that the mineral is optically isotropic and enables one to recognize octahedra from the crystal outlines. Fig. 13 illustrates some of the characteristic shapes. Fig. 10 shows the cross section of a twin, which corresponds well with the shape and angles of spinel twins. The re-entrant interfacial angle of the twin was measured in the plane of the polished section, in several specimens, and the highest values found approach the calculated angle of the spinel twin, namely 141° 04′. Ramdohr has illustrated spinel as an unmixing product in titano-magnetite.

The spinel occurs as lath-shaped, rounded, subhedral, or euhedral grains. The elongate lath or spindle shapes are most numerous. Spinel occurs only in the magnetite, ilmenite grains being conspicuously free from spinel inclusions. In places spinel may be observed as rows of subhedral grains, lined up along the contact of magnetite with ilmenite or silicates. This evidently represents partial segregation to grain boundaries after unmixing.

The grains in which the spinel occurs appear at low magnifications to be simply magnetite, but at magnifications of several hundred to one thousand diameters a very fine and somewhat irregular intergrowth of magnetite and ilmenite may be observed (Fig. 10). In these grains larger lamellæ of ilmenite are absent.

Rutile occurs abundantly in some ilmenite deposits and this is particularly true of the St. Urbain region, about 250 miles south-west of Sept-Iles. At the latter deposits rutile was observed only as occasional accessory grains and it is probably not significant.

Genesis of the Abnormal Intergrowths.—The mode of origin of the microstructure described above is of considerable interest for the understanding of ex-solution phenomena. The evidence

cited indicates that the ilmenite was not precipitated along octahedral planes prior to their distortion. That such distortion might happen during dynamic metamorphism seems a reasonable inference and the possibility had to be considered.

The relations of magnetite and ilmenite in ores have been very carefully described and experimental work has verified their mutual solubility at high temperature. Application of previously suggested criteria [16] makes a rather clear-cut case in favor of exsolution as the mode of origin of the textures described above. In the Sept-Iles deposits, however, complicating factors were at work and an unusual intergrowth resulted.

The arrangement of the ilmenite lamellæ suggests an offset in the planes along which the ilmenite later segregated. The fact that a major portion of the lamellæ lie in parallel planes suggest that conditions of crystallization were not equally favorable in all directions.

Magnetite crystallizes early in magmas, and in basic magmas the temperature is usually considered to be fairly high. In any event it is not higher than the melting point of pure magnetite (1540° C) and probably is appreciably lower.

Kamiyama [17] reported that melting in titaniferous magnetite from Korea occurred at 1390° C ± 10°. Data on the unmixing temperature of ilmenite from magnetite are not conclusive. Kamiyama found that ilmenite dissolved when held above 1150° C, but natural specimens segregated more completely when kept in a range below 1150° C. Ramdohr [18] described experiments which indicate that solution of ilmenite occurs between 600° and 700°. These data seem quite incompatible, yet, as Greig [19] has pointed out, impurities may make a large difference in the temperatures at which such changes take place.

[16] Schwartz, G. M.: Textures due to unmixing of solid solutions. ECON. GEOL., 26: 739–763, 1931.

[17] Kamiyama, M.: Report on a heating experiment with titaniferous magnetite from Korea. Jour. Geol. Soc. Tokyo, 36: 12–29, 1929.

[18] Op. cit., p. 374.

[19] Greig, J. W.: Temperature of formation of the ilmenite in the Engels copper deposit. ECON. GEOL., 27: 25–38, 1932.

Available facts, therefore, suggest that the distortion of the planes along which the ilmenite segregated has taken place between the time of crystallization of the magnetite and the time of ex-solution of the ilmenite. The concentration of the lamellæ mainly in one series of parallel planes suggests that some stress was active during ex-solution. The intrusion and cooling of a mass of gabbro is necessarily accompanied by considerable dynamic disturbance. It is, therefore, not surprising that the partly cooled gabbro and associated rocks should have been subjected to stress.

As the temperature fell and ilmenite began to ex-solve, it took up positions along planes that had been subject to extensive, closely spaced slipping or translation.[20] Crystallographic planes at an angle to the plane of translation would be offset and thus perhaps account for the en échelon arrangement of the ilmenite inclusions. Where the deformation was more complicated, curved and irregular arrangement of the inclusions resulted. If the deformation had taken place subsequent to ex-solution the lamellæ would be offset with the planes. The only difference to be expected would be an actual shearing of individual inclusions.

Why the basal lamellæ of ilmenite crystallize in the direction of the octahedral planes of magnetite is easy to understand. It is a case of mutual orientation of crystals, similar to *epitaxy* in some respect. The lattice net of the ilmenite lamellæ is hexagonal, like that of the octahedral planes. Moreover the unit-mesh (plane unit-cell) of the one is close enough in size to that of the other to permit an oriented intergrowth.

UNIVERSITÉ LAVAL,
QUEBEC, CANADA,
June 16, 1941.

[20] *Translation* or "translation-gliding," as opposed to *gliding* or "twin-gliding" or simple shear (einfache Schiebung).

THE MISSISSIPPI VALLEY TYPE LEAD-ZINC DEPOSITS AND THE PROBLEM OF MINERAL ZONING.

R. M. GARRELS.

ABSTRACT.

The position of minerals in hypogene veins has little apparent relation to mineral solubility. This problem is attacked by a detailed study of the Mississippi Valley type lead-zinc deposits, in which galena has behaved as if it were more soluble than sphalerite. Several possible explanations of this behavior are advanced, but the increase in galena solubility is attributed chiefly to the formation of chloride complexes. Experimental work shows that concentrated chloride solutions (2 molal) are necessary to explain the observed mineral relations. Evidence is presented to show that high concentrations may be a common feature of hypogene solutions.

THE PROBLEM OF MINERAL ZONING.

An important problem in economic geology is the mechanism that controls metal sulphide zoning. Although this subject has received much attention recently,[1] no entirely satisfactory explanation has yet been advanced. It is generally agreed that minerals are carried in true solution in hypogene water,[2] yet the metal sulphides do not precipitate in the order that would be expected from their relative solubilities. It is a well-known fact that galena and argentite, two of the least soluble of the sulphides, are carried much farther from their source than the more soluble zinc and iron sulphides.

The problem is difficult to attack because of the multi-component chemical system that must be investigated if vein-forming conditions are to be simulated, and because of the paucity of

[1] *Cf.* Bandy, Mark: A theory of mineral sequence in hypogene ore deposits, part I. Econ. Geol., 35: 359–382, 1940. Part II: ibid., pp. 546–571.

[2] Graton, L. C.: The nature of the ore-forming fluid. Econ. Geol., 25 (supplement): 212, 1940.

knowledge at present of the equilibria that exist at the high temtemperatures and pressures characteristic of so many hypogene deposits.

Because of these difficulties, it was decided that the most promising method of attack was an investigation of the simplest type of deposit in which this anomalous zoning has been observed—the Mississippi Valley type lead-zinc ores. Not only is the mineralogy of these deposits simple, but the physico-chemical conditions of their formation are within the range of ordinary chemistry, and some fairly accurate data are at hand as to the nature of the metallogenic solutions and the temperatures and pressures at the time of sulphide deposition.

Although there is still a great deal of controversy over the origin of these deposits,[3] two of the most probable theories (ascending magmatic waters or ascending artesian waters) are faced by the explanation of the mineral zoning. In these deposits galena generally occurs nearer the surface than sphalerite, and this order is ascribed to primary zoning.[4] Since galena has a smaller solubility product than sphalerite,[5] and is generally conceded to be less soluble, it should be expected to precipitate from the ascending solutions before sphalerite, and hence be found deeper in the veins and earlier paragenetically than sphalerite, whereas in fact the reverse is true.

The explanation of this reversal of the expected order of precipitation in the Mississippi Valley type of deposits may well be expected to cast light on similar reversals in the deposits of undisputed hypogene origin.

The plan of attack is: (1) postulation of the physico-chemical environment of deposition; 2 appraisal of the explanations possible under these conditions; (3) quantitative investigation of the most probable explanation.

[3] Bastin, E. S. (edit.): Contributions to a knowledge of the lead-zinc deposits of the Mississippi Valley. G. S. A., Spec. Pap. 24: 121, 1939.

[4] Bastin, E. S., *op. cit.*, p. 137.

[5] Verhoogen, Jean: Thermodynamical calculation of the solubility of some important sulphides, up to 400° C. Econ. Geol., 33: 47, 1939.

PHYSICO-CHEMICAL ENVIRONMENT OF DEPOSITION.

Temperature and Pressure.—The temperature and pressure of formation of lead-zinc deposits of the Mississippi Valley type can be defined with reasonable accuracy. Newhouse [6] has determined the temperature of formation to be between 90 and 135° C.; the Joplin deposits being formed at the top of this range, the Wisconsin-Illinois deposits at the bottom.

Since the exact age of the deposits is not known [7] it is difficult to ascertain the depth of formation. However, the greatest possible depth is in the Wisconsin-Illinois region, where a maximum of 2000 feet of rock covered the deposits at the time of formation. Such a depth, assuming that fractures extended to the surface, would represent a hydrostatic pressure of $\frac{2000}{34} = 60$ atmospheres.

Components of the Vein Solutions.—A postulation of the chief constituents of the vein solutions can be made from the important primary minerals and from analogies with ground waters, mine waters, and the products of fumaroles. The only minerals present in appreciable quantities in the deposits are galena, sphalerite, pyrite, chalcopyrite, marcasite, calcite, dolomite and fluorite. From these, the presence of lead, zinc, iron, copper, calcium, magnesium, sulphur, oxygen, carbon, and fluorine can be deduced. These components are purposely listed in the form of elements, for they may have existed in solution in all possible ionic species—as Pb^{++}, Zn^{++}, $PbCl^{+}$, ZnF^{+}, $CaCl^{+}$, and in many other combinations.

From a general survey of analyses of ground and mine waters, and of the products of fumaroles, a few important additions can be made; they are hydrogen, sodium, boron and chlorine.

This list, although it probably is one of the simplest chemical systems from which hypogene vein deposits have been formed, is still too complex to handle with complete quantitative precision.

Chemical State of the Vein Solutions.—From the components

[6] Newhouse, W. H.: The temperature of formation of the Mississippi Valley lead-zinc deposits. ECON. GEOL., 28: 740–750, 1933.

[7] Bastin, E. S., *op. cit.*, p. 132.

listed above, the temperature and pressure mentioned, and from additional geological evidence, some generalizations can be made about the number of phases, the acidity or alkalinity, and the presence of an oxidizing or reducing environment in the solutions.

Number of Phases.—The pressure and temperature of deposition (ca. 60 at. and 100° C.) assure the presence of not more than two phases—solid and liquid. Much higher temperatures are necessary to produce a gas phase at such a pressure. Thus, the perplexing problem of vapor transport of metals does not enter into the discussion. It is quite probable, however, that solids were present as colloids. This possibility will be considered later.

Acidity of the Solutions.—The pH, or acidity of the solutions, can be fairly well established. The presence of marcasite and pseudomorphs of sphalerite after wurtzite suggest that the solutions were acid, for marcasite and wurtzite are usually stable in acid solutions.[8] Furthermore, deposition is generally accompanied by solution of calcite and dolomite, and the localization of the deposits in carbonate rocks points to the mechanism of neutralization of hydrogen ion by reaction with the carbonate, with the subsequent release of sulphide ion and precipitation of the metal sulphides. This acidity could not have been great, however, for cases are on record of the simultaneous deposition of calcite and sulphides.[9] Also, pyrite and marcasite have been found in the same vein, the pyrite marginal, showing a shift from alkaline to slightly acid waters.[10] Furthermore, primary inclusions in the galena were tested by Newhouse,[11] and neither acid nor base could be detected by litmus paper.

The sum of this evidence indicates that the solutions were

[8] Allen, E. T., Johnson, John, and Larsen, E. T.: The mineral sulphides of iron. Amer. Jour. Sci., 4th ser., 33: 169–236, 1912. Allen, E. T., Crenshaw, L. J., and Merwin, H. E.: The sulphides of zinc, cadmium and mercury. Amer. Jour. Sci., 4th ser., 34: 341–396, 1912.

[9] Bastin, E. S., *op. cit.*, p. 117.

[10] Behre, C. H., Jr., Scott, E. R., and Banfield, A. F.: The Wisconsin lead-zinc district, preliminary paper. Econ. Geol., 32: 803, 806, 1937.

[11] Newhouse, W. H.: The composition of vein solutions as shown by liquid inclusions in minerals. Econ. Geol., 27: 428, 1932.

slightly acid as they rose, and very nearly neutral at the time of deposition.

Oxidizing or Reducing Environment.—The reducing nature of the environment is easily established by the presence of ferrous ion (pyrite), plumbous lead (galena), and the absence of sulphates.

Recapitulation.—The material on the environment of deposition makes it possible to define the problem of the Mississippi Valley type ores in more precise chemical terms: is there any reason why galena should appear more soluble than sphalerite in a slightly acid solution of lead, zinc, iron, copper, hydrogen, magnesium, calcium, sodium, boron, chlorine, sulphur and fluorine at a temperature of 100° C., a pressure of 60 atmospheres, in a reducing environment?

REASONS FOR REVERSAL OF THE EXPECTED GALENA-SPHALERITE ORDER OF DEPOSITION.

Even with the fairly definite limitation of conditions just established, the solution of the problem necessarily varies with assumptions regarding whether chemical equilibrium was maintained in the solutions, and whether one or two phases were present. The important combinations of these possibilities will be treated under the three following headings: (1) chemical equilibrium maintained, solid and liquid phases present; (2) chemical equilibrium not maintained, liquid phase present; (3) chemical equilibrium maintained, liquid phase present.

Chemical Equilibrium Maintained, Solid And Liquid Phases Present.—On the assumption that both solid and liquid phases were present the zoning can be explained by the mechanism of colloid transport. Both galena and sphalerite may have precipitated at depth as colloids, remaining in suspension. Under this hypothesis, galena precipitated first, and the more soluble sphalerite afterwards. However, since the zoning depends upon the place of deposition, rather than upon the place of precipitation for colloids, both sulphides may have been carried for a considerable distance in the solid form. Presumably the present zoning would be due, in this case, to the earlier flocculation of sphalerite.

This reduces the problem to one of colloid stability rather than true sulphide solubility.

Such an explanation might be valid in the Wisconsin-Illinois region, or in many of the European districts, where colloform textures are common,[12] but the well-crystallized nature of the great majority of the Mississippi Valley deposits appears to make such an explanation unsatisfactory as a general thing. It would be impossible to tell, in the event that colloform textures were everywhere prevalent, whether they were the result of *precipitation* of colloids only, or of *transportation* as colloids as well.

Chemical Equilibrium Not Maintained, Liquid Phase Present.—If it is assumed that chemical equilibrium was not maintained, the zoning can be accounted for by supersaturation phenomena. If, as the solutions rose, the solubility of galena was exceeded but precipitation failed to occur, galena might stay in solution in a metastable state until sphalerite had been precipitated, and would, therefore, act as if it were more soluble.

The degree of probability for such an occurrence is not known, but there is considerable geological and chemical evidence to suggest its possibility. The common occurrence of zoned feldspars shows that equilibrium is not always maintained, at least in magmatic solutions. Furthermore, Kolthoff[13] has shown that the length of time before a supersaturated solution comes to equilibrium depends upon the catalytic effect of the various ions present. Copper ion, for instance, is a well-known precipitant of zinc sulphide from supersaturated solutions, and the presence of a little copper ion in the Mississippi Valley vein solutions might well have been expected to cause the precipitation of sphalerite first, while galena continued in the metastable state.

Chemical Equilibrium Maintained, Liquid Phase Present.—

[12] Behre, C. H., Jr., Scott, E. R., and Banfield, A. F.: The Wisconsin lead-zinc district, preliminary paper. ECON. GEOL., 32: 804–805, 1937; Behre, C. H., Jr., European colloform ores of Mississippi Valley Type (abstr.). G. S. A., Bull., 49: 1866–1867, 1938.

[13] Kolthoff, I. M., and Pearson, E. H.: The promoting action of CuS on the speed of precipitation of ZnS. The so-called co-precipitation of zinc with copper sulphide. Jour. Phys. Chem., 36: 549–566, 1932.

The assumption that equilibrium was maintained and that a single phase (liquid) was present yields an hypothesis of zoning that can be rigorously treated chemically. This hypothesis is that lead sulphide was prevented from precipitating first by the presence of lead complexes in the solution, which increased the solubility of galena beyond that of sphalerite. This is analogous to the prevention of the precipitation of silver chloride by the addition of ammonia to a silver-bearing solution with the resultant formation of a soluble ammonia-silver complex.

Thus, if one or more of the constituents of the vein solution formed a complex with lead, sphalerite might be precipitated first and correspondingly deeper in the deposits.

Selection of Complexes as the Problem for Attack.—Of these three possibilities—complexes, supersaturation and colloids—complexes were selected for a quantitative appraisal. Colloids were dismissed because of the well-crystallized nature of most of the deposits. Supersaturation and complexes seemed equally feasible explanations, but the formation of complexes was selected for attack because of evidence from chemical and geological literature that suggested that such a mechanism might have been effective.

INVESTIGATION OF THE EFFECT OF COMPLEXES ON GALENA-SPHALERITE ZONING.

Before specifically investigating complexes and their effect on mineral zoning, it is desirable to discuss the properties of the vein solution in terms of modern ionic theory. The author also wishes to show the value of applying the thermodynamic concept of the "activity" of ions to problems in ore deposition.

The components of the solution and the environment of deposition have already been postulated. The problem that lies ahead is the determination of the way in which lead and zinc were held in solution. Since the deposits, taken as a whole, contain roughly equal amounts of sphalerite and galena, it is safe to assume that equivalent amounts of lead and zinc were being transported together to the place of deposition.

However, the factor that controls the precipitation of a metal

sulphide from solution is not the amount of metal dissolved (total concentration), but the effective concentration of the metal ion (activity). In dilute solutions ($>$ 0.1 m.) these two values are close enough to each other to ignore the difference for most practical purposes, but in more concentrated solutions the variation may be tremendous. Sometimes the effective concentration is less than the total, sometimes it is much greater.[14] Furthermore, the direction and magnitude of variations almost defy predication; experimental work is necessary for security.

The Relation Between "Activity" and Complexes.—A complex may be conveniently defined as any ionic species that reduces the activity of an ion in solution. For instance, returning to the example of the addition of ammonia to a silver-bearing solution, the addition of ammonia to silver nitrate solution is effective in preventing precipitation of silver chloride when chloride ion is later added to the solution because the ammonia has reduced the effective concentration of silver ions so much that there are not enough active silver ions left to join with the chloride ions. The same amount of silver is still in the solution, but it has been rendered incapable of reacting as silver ion. It is not generally necessary to know the type of the complex formed; the effect on the solubility is known if the change in the activity of silver ion is determined.

Also, it is usually more convenient to determine the ratio of the activity to the total concentration than to express the activity alone. This ratio of activity to concentration is known as the activity coefficient γ, or as the thermodynamic degree of dissociation.[15]

This can be further illustrated by application to vein solutions. It is known that lead and zinc are present in equal total concentrations. If the solution be pictured as it is generally conceived by geologists—with all the lead and zinc in the form of simple

[14] As in concentrated $FeCl_3$, where the apparent ionization is several hundred per cent.

[15] Lewis, G. N., and Randall, Merle: Thermodynamics. McGraw-Hill Book Co., New York, 1923, p. 328.

metal ions, there would be then an equal amount of lead and zinc capable of reacting with the sulphide ion in the solution, and, since it takes only $\frac{1}{10,000,000}$ as much effective lead ion to unite with sulphide ion as it does zinc at 100°,[16] galena would be precipitated long before sphalerite.

However, if one or more of the components of the solution reduce the activity of lead ions, or increase the activity of zinc ions, the result will be a tendency for galena to stay in solution longer, or for sphalerite to come out sooner. The important thing, however, is for the component, whatever it may be, to affect lead and zinc differentially. If this differential effect were great enough, and the ratio of the activities of lead and zinc ion was reduced to $Pb^{++} = 1 : Zn^{++} = 10,000,000$, then galena might be expected to precipitate before sphalerite, as in nature.

Chlorides As The Probable Complex-Formers.—In light of the preceding considerations a search was made through the chemical literature to determine which of the vein solution components had a differential effect on lead and zinc activities. This study showed that chloride ion was the only constituent that had an effect of a magnitude near that necessary to cause the reversal of zoning.

The importance of chloride ion complexes is strikingly corroborated by further geological and chemical evidence. Newhouse [17] has shown that galena from these deposits contains primary liquid inclusions that are strong solutions of sodium chloride. Ralston [18] writes of several hydrometallurgical processes in which galena is leached from sphalerite by hot concentrated brine solutions. Dede and Bonin [19] found that the presence of neutral

[16] Verhoogen, Jean: Thermodynamical calculation of the solubility of some important sulphides, up to 400° C. ECON. GEOL., 34: 47, 1939.

[17] Newhouse, W. H.: The composition of vein solutions as shown by liquid inclusions in minerals. ECON. GEOL., 27: 428, 1932.

[18] Ralston, O. C.: Hydrometallurgy of lead. A. I. M. E. Trans., 70: 452, 1924.

[19] Dede, L., and Bonin, P.: Inhibition of metal sulphide precipitates by means of neutral chlorides. Ber. Deutsch. Chem. Gesell., 55b: 2327–2331, 1922.

chlorides (chlorides that do not hydrolyze appreciably) inhibited the precipitation of PbS from acid solution. They suggested that the cause for this apparently anomalous behavior is the formation of complexes.

The pressure of all these indications led the author to make a quantitative study of the effect of various chlorides on lead and zinc ion activities.

Results of the Study of Lead and Zinc Activities in the Presence of Chlorides.—The details of the theory of ion activity determinations and the experimental methods used are included in a much longer paper on the subject by the author.[20] Also, the experimental material has been prepared for publication in the Journal of the American Chemical Society.[21] However, it may suffice here to say that the experiments were carried out, using precise chemical methods, under the direction of Dr. F. T. Gucker, Jr., of the Chemistry Department at Northwestern University.

The results of the work may be summarized as follows: (1) the addition of chloride ion to a solution containing lead and zinc first depresses both the zinc and lead ion activities, but above concentrations of 0.1 molal added chloride, the activity of zinc ions increases, while that of lead ions continues to decrease. (2) The effect described is independent of the type of chloride present, whether it be sodium, potassium, or calcium, and depends only upon the concentration of effective chloride ion. (3) The effect is greater at higher temperatures, approximately doubling with a temperature change from 25° to 65° C. (4) At 100° C. (approximately the temperature of formation of the Mississippi Valley deposits) the lead ion activity is reduced to $\frac{1}{10{,}000{,}000}$ of of the zinc ion activity by a concentration of 2.0 molal ($\pm$ 0.2 m.) added chloride.

[20] Garrels, R. M.: Factors influencing the deposition of galena and sphalerite in the Mississippi Valley lead-zinc deposits. Ph.D. Thesis, Northwestern Univ. (unpub.).

[21] Gucker, F. T., Jr., and Garrels, R. M.: Activity coefficients of lead chloride in the presence of sodium chloride, from 35 to 65° C. (submitted for publication).

The curves of Fig. 1 show the effect of the addition of sodium chloride on the activity coefficient of lead and zinc ions. Since the activity coefficient of the metal ion is the ratio of the effective concentration of metal ion to the total concentration of metal, a

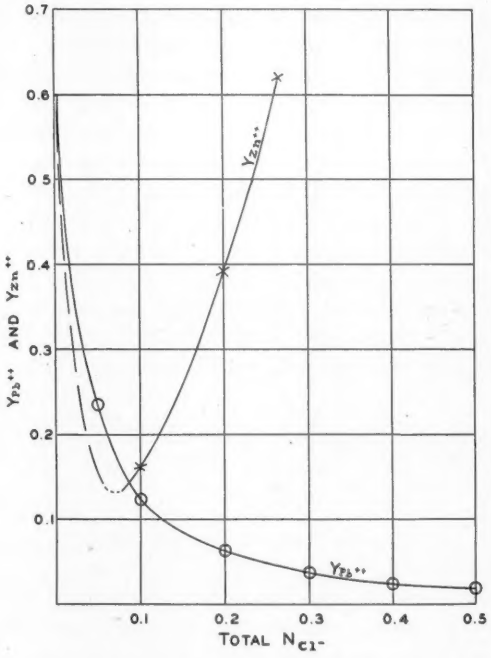

FIG. 1. Plot showing relation of lead and zinc activity coefficients to neutral chloride concentration.

decrease in the activity coefficient means that progressively more effective metal ion is tied up in complexes of one form or another, and, consequently, the solubility of the metal is increased. Fig. 1 shows that the addition of sodium chloride to a solution of lead and zinc first increases the solubility of both metals until the solution becomes 0.1 molal in chloride, but above 0.1 molal lead con-

tinues to increase in solubility, while zinc rapidly decreases. It is from these and similar curves that the conclusions above are drawn.

This means that, if the vein solutions contained 2.0 molal or more concentrated chloride, the zinc ion activity would be so increased, and the lead ion activity so depressed, that sphalerite would precipitate from such a solution before galena.

This may be visualized in the following way. Suppose that the vein solutions contained 0.001 mols of both lead and zinc (total concentration). In the presence of 2.0 molal chloride in the solution, the zinc and lead would act, toward the sulphide, as if there were 10,000,000 times as much zinc as lead. Since the zinc ion activity is increased, while the lead ion activity is decreased, the solution would probably react *as if there were* 0.1 mols of zinc ion present, and only 0.00000001 mols of lead ion.

Thus, if it can be shown that there is reason for assuming the presence of chlorides in the concentrations indicated, the mechanism of complex ions may well be the one that caused the observed zoning.

EVIDENCE SUPPORTING HIGH CONCENTRATIONS IN VEIN SOLUTIONS.

Geological Evidence.—At first the necessity for having concentrations as high as 2 m. seemed to the author to be an argument against the mechanism of chloride complexes as an explanation of the reversal of the anticipated order of precipitation, as illustrated in lead-zinc deposits and especially in those of the Mississippi Valley type. For instance, Graton says,[22]

> It must be remembered that with anything like the low concentrations of solutes which *most of us* regard as reasonable, whether gas or liquid be the transporting agent, countless volumes of hot fluid would have to pass by any given foot of channelway before accomplishing the deposition of one volume of material.

However, the only direct evidence of the composition of the solutions diametrically opposes the picture presented by Graton.

[22] Graton, L. C.: The nature of the ore forming fluid. ECON. GEOL., 25 (supplement): 231, 1940.

Newhouse [23] found concentrations of sodium chloride of 200 grams per liter, or about 4 molal. This is more than sufficient chloride to cause the observed zoning of the sulphides.

Furthermore, the work here described led the author to make a critical survey of the literature on vein solutions, and much of the evidence seemed to point toward concentrated rather than dilute solutions.

Complexes as a General Mechanism of Metal Transport.—The very low solubilities of the metal sulphides have long been a stumbling block to the economic geologists in their attempts to postulate the types of solutions from which hypogene ores have been deposited. Despite the opinions of Lindgren [24] it seems to be generally agreed that colloids are not important in vein formation,[25] and this made it necessary to find a method by which metals and sulphides could be carried together in true solution. This has become increasingly difficult as more exact determinations of sulphide solubilities have been made. Indeed it was found that early workers had enormously exaggerated the true solubilities.[26]

From a purely theoretical standpoint it does not seem possible that a dilute solution, whether acid, alkaline, or neutral, can carry any appreciable amount of metal, for in dilute solutions ionization is great, and any metal present is almost entirely in the form of ions effective in causing precipitation. Consequently, traces of metal and sulphide will immediately precipitate.

One group of geologists attempted to circumvent this difficulty by assuming the solutions to be strongly acid: thus precipitation would be prevented by the repression of the sulphide ion. Not only does this call for high concentrations, but it was pointed out that free acids would soon be neutralized by wall rock.[27] There

[23] Newhouse, W. H.: The composition of vein solutions as shown by liquid inclusions in minerals. ECON. GEOL., *27*: 428, 1932.

[24] Lindgren, Waldemar: Mineral Deposits. McGraw-Hill Book Co., New York, 1928, p. 190.

[25] Graton, L. C.: *op. cit.*, p. 212.

[26] Kolthoff, I. M.: Solubilities and solubility products of metallic sulphides in water. Jour. Phys. Chem., *35*: 2711–2721, 1931.

[27] Graton, L. C.: *op. cit.*, p. 294.

is some evidence of such neutralization in certain ores, but the scale of alteration is quite insufficient to justify the assumption of a highly acid solution.

The alternative suggested was dilute alkaline solutions.[28] The suggestion is surprising in light of the fact that metal sulphides reach their minimum solubility in such an environment. Metals are dissolved in alkaline solutions in much the same way as in chloride solutions—a complex is formed which represses the activity of the metal ion. Dreyer,[29] in the case of mercury, showed that the complex is probably of the form $MeS_2^{=}$. It is fairly obvious that the formation of this complex depends upon an excess of sulphide ions in the solution, which force the sulphide into the complex form. If a metal sulphide is put into solution, and sulphide is added, the sulphide ions first decrease the solubility of the metal sulphide because of the common ion effect; then, as the concentration of the sulphide ions is further increased, they begin to force the sulphide over into the soluble complex. The concentration of sulphide ions that must be added to cause an increase in solubility depends, of course, on the activity product of the sulphide and the ionization constant of the complex, but it is fairly safe to assume, from analogy with the complexes discussed in this paper, that at least 0.3 to 0.4 molal sulphide ion is necessary. Thus, the solution is not dilute at all, but concentrated.

The author believes that the concept that metals can be transported in *dilute* alkaline solutions grew partly from the unjustified conclusion that behavior in dilute solution differed from behavior in concentrated solution only in degree, and partly from the misinterpretation that metals held in alkaline solutions as colloids are in true solution.[30]

Thus, it appears that in true solutions, whether alkaline or acid, relatively high concentrations must be present before metals can be effectively carried, and solutions in both alkaline and acid media

[28] Graton, L. C.: *op. cit.*, p. 231.

[29] Dreyer, Robert: The geochemistry of quicksilver mineralization, Part I. ECON. GEOL., 35: 28, 1940.

[30] Stevens, R. E.: Alteration of pyrite to pyrrhotite by alkali sulphide solutions. ECON. GEOL., 28: 1–5, 1933.

depend upon the formation of complexes. A further reason for accepting complexes as means for metal transport is that they afford a convenient means of deposition that does not depend on wall rock reaction or upon temperature drop. If a concentrated vein solution is diluted by ground water, the metals in the complexes are released, and precipitation will take place. Also, the ponding of a concentrated solution beneath an impervious rock, a commonly cited method of ore formation,[31] is much more likely to result in the deposition of appreciable quantities of metallic minerals than is a dilute solution, which should have a " flushing " action on any material already precipitated.

Conclusion Regarding Concentrated Solutions.—Because, (1) concentrated solutions are apparently necessary in most deposits of undisputed hypogene origin, and (2) the direct evidence of Newhouse's work supports high concentration, it is assumed that chloride ions may well have been the determining factor in the reversal of zoning order found in the Mississippi Valley or other similar lead-zinc deposits.

SUMMARY.

It has been shown that concentrated chloride solutions could have been responsible for the apparently anomalous primary zoning of galena and sphalerite in the Mississippi Valley type lead-zinc ores. It is not assumed from this that chlorides represent a universal solution of mineral zoning problems. However, it was pointed out that if the usual assumptions of the maintenance of chemical equilibrium and lack of colloids are made, dilute solutions of any type seem hopeless as metal carriers.

In view of this, the author believes that the solution of the zoning problems in shallow deposits of hypogene origin must be explained either on the basis of concentrated solutions, or must be relegated to the category of problems in unstable equilibrium.

ACKNOWLEDGMENTS.

This work was carried on under the auspices of the Chemistry and Geology and Geography Departments of Northwestern Uni-

[31] Bain, G. W.: Mechanics of metasomatism. ECON. GEOL., 31: 505–526, 1936.

versity. The author wishes to thank Dr. F. T. Gucker, Jr., of the Chemistry Department and Dr. C. H. Behre, Jr., of the Geology Department for their constant direction and guidance.

Parts of the manuscript were read, and helpful criticisms offered, by Dr. L. H. Adams of the Geophysical Laboratory; Dr. T. S. Lovering of the Department of Geology of the University of Michigan; Dr. Malcolm Dole of the Department of Chemistry of Northwestern University; and Dr. A. L. Howland of the Geology Department of Northwestern University.

NORTHWESTERN UNIVERSITY,
EVANSTON, ILLINOIS,
July 16, 1941.

TITANIFEROUS SANDSTONE NEAR BUENA VISTA, VIRGINIA.[1]

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ABSTRACT.

A lenticular fossil placer deposit of titaniferous minerals, discovered in 1939 near Buena Vista, Virginia, suggests that future studies might disclose some tin-bearing sandstone along the western flanks of the Blue Ridge.

A LENTICULAR concentration of titaniferous minerals at the base of the Unicoi formation was discovered during the summer of 1939. The deposit is exposed on the Robinson Gap road about 3 miles southeast of Buena Vista, Rockbridge County, Virginia (Fig. 1).

According to the prevailing classification[2] the Unicoi is the lowest Cambrian formation along the east side of the Appalachian Valley in Virginia. It is characterized at the base by about 100 feet of arkosic sandstone and conglomerate. In the Robinson Gap section these sediments contain about 4 feet of red volcanic tuff, approximately 15 feet above the unconformity at the base of the formation. The lower 15 feet of the Unicoi contains titaniferous sandstone in black bands from one-fourth to 6 inches thick, interbedded with red-brown, medium-grained, arkosic sandstone.

The Unicoi formation lies on coarse-grained granodioritic migmatite that contains irregular zones of aplitic material. The migmatite appears uniformly green and massive in fresh exposures, but weathering produces a light-gray color and reveals foliation.

The titaniferous sandstone occurs in a lens about one-fourth mile long on the northwest limb of the Buena Vista anticline.

[1] Published with permission of the State Geologist of Virginia.

[2] Butts, Charles: Geologic map of the Appalachian Valley of Virginia with explanatory text. Virginia Geol. Surv. Bull. 42: 2, 1933.

This structure strikes about N. 45° E. and dips about 30° NW. The sandstone apparently occupies an ancient depression in the erosion surface beneath the Unicoi formation.

Hand specimens of the titaniferous sandstone are unusually heavy. The rock is black, with intervening layers of red-brown, arkosic material. Microscopic examination reveals that rutile and ilmenite (Fig. 2) comprise about 50 per cent of the rock. Ilmenite replaces rutile along fractures and around the periphery

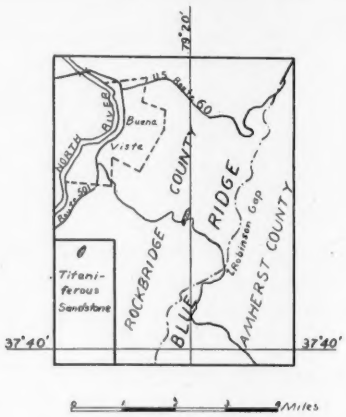

FIG. 1. Occurrence of titaniferous sandstone along the west flank of the Blue Ridge in central-western Virginia.

of well rounded grains. These grains average about half a millimeter in diameter. Other minerals in the sandstone include quartz and feldspar and accessory zircon, tourmaline, and apatite.

A reconnaissance survey with a magnetometer made by G. R. MacCarthy showed that the titaniferous sandstone corresponds to an inconspicuous magnetic high. Plus anomalies plotted on a sketch map form a roughly lenticular outline that closely follows boundaries determined on the basis of outcrops.

Rutile and ilmenite are common accessory constituents in the granodioritic migmatite. The titanium minerals in the sandstone were probably derived from this source. The disseminated ti-

tanium ores near Roseland and Piney River, Virginia,[3] are located approximately 30 miles northeast of the Robinson Gap deposit. Presumably, the titaniferous sandstone represents a lithified placer deposit.

Although cassiterite has not been identified from the Robinson Gap deposit its occurrence in pegmatitic rocks on Irish Creek,[4] in the northern part of Rockbridge County, 12 miles northeast

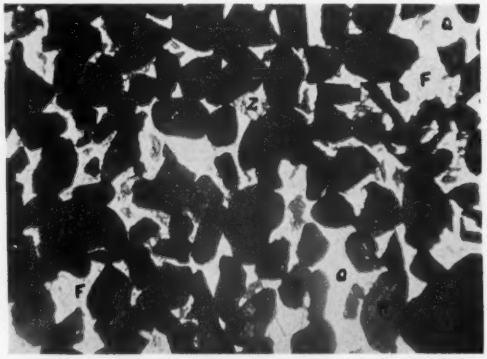

FIG. 2. Titaniferous sandstone showing rutile (R), ilmenite (I), quartz (Q), feldspar (F), and zircon (Z). $\times 61$.

of Robinson Gap, suggests the possibility of a similar concentration of tin minerals. Sedimentary environments during the early Cambrian in the Irish Creek area were no doubt similar to those near Robinson Gap, thus, future detailed stratigraphic and petrographic studies might disclose some tin-bearing sandstone along the western flanks of the Blue Ridge.

UNIVERSITY OF NORTH CAROLINA,
CHAPEL HILL, N. C.,
May 15, 1941.

[3] Watson, T. L. and Taber, Stephen: Geology of the titanium and apatite deposits of Virginia. Virginia Geol. Surv. Bull. III–A: 56–201, 1913. Ross, C. S., Titanium and soapstone deposits: Internat. Geol. Cong., XVI, United States, 1933, Guidebook 11, pp. 29–36, 1932.

[4] Ferguson, H. G.: Tin deposits near Irish Creek, Virginia. Virginia Geol. Surv. Bull. XV–A, 19 pp., 1918.

DISCUSSION AND COMMUNICATIONS

A NEW HELVITE LOCALITY—A POSSIBLE BERYLLIUM DEPOSIT.

(*Preliminary Report.*)

Sir: In September 1940, I obtained three ore specimens from a miner in New Mexico. The specimens were labeled "iron," "zinc ore" and "fluorite" by him. These minerals came from a property 10 miles north of Chloride, New Mexico, where a small amount of gold had been found usually associated with bismuth. The discovery of the zinc ore on the property aroused some interest for both its zinc content and possible association with other rarer minerals.

A photographed optical spectrum of the fluorite showed extremely strong beryllium lines, equivalent to about 2% Be. The hand specimen was essentially colorless granular fluorite darkened by admixed magnetite particles, with no other mineral visible.

The property has now been systematically prospected and all characteristic rocks and ores examined spectrographically by me for Be. I have isolated and identified the mineral carrying the Be as *Helvite* by a spectrographic analysis of microscopically isolated fragments of the mineral, its optical properties, specific gravity and crystal form. This is the fourth reported occurrence of helvite in the United States as far as I can discover in the literature.

The mineral helvite is an isomorphic mixture of three theoretical end members:

Manganese	helvite	3	Mn	Be	SiO_4	+	MnS
Iron	helvite	3	Fe	Be	SiO_4	+	FeS
Zinc	helvite	3	Zn	Be	SiO_4	+	ZnS.

A detailed report on the deposit and its minerals is being prepared.

The deposit was visited in October 1940, and in the several tons of ore removed from the body richest in Be, brown-red helvite occurs in numerous veins and pockets in the ore; as well as granules forming a major constituent of a "helvite rock." Pieces weighing several pounds containing up to 50% helvite are numerous, while hand specimens of nearly pure helvite contain typical tetrahedral crystals up to 8 mm. have been found. The ore in one body averages nearly 3% BeO, or 15 to 20% helvite. The other minerals identified are abundant magnetite, hematite, colorless fluorite and feldspar, minor amounts of pyrite and bismuthinite containing gold.

The Be-rich zone follows a deep ravine which is apparently a fissure fault in the contact metamorphosed limestone beds. Two Be-rich ore bodies have been located in this zone at about 500 ft. apart, while a third one lies an equal distance up on the ravine slope nearer the garnetite zone beneath the several hundred feet of garnetite-magnetite, and overlying massive magnetite (3% Mn, no Ti and only a trace of P).

This third ore body higher up on the ravine slope consists of irregular veins and pockets of purple fluorite, which contain a smaller and less constant amount of Be. The Be mineral here has been identified as a lemon-yellow variety of helvite which is much richer in Mn and poorer in Fe than the brown-red variety. A second Be mineral has been found associated with this purple fluorite and pyrolusite body. It consists of radiating clusters of prismatic crystals (about 1 mm. thick) with a green tinged white color resembling datolite and a habit of Scolecite. Whether or not this represents a new Be mineral has not yet been ascertained. A micro gravity determination on 4.7 mgs. of pure isolated fragments give a gravity of 3.72. A qualitative spectrographic analysis showed the following major constituents: Ca, Mg, Be, Al, Si, Fe (Mn) but no Na, P, B, or As.

The field prospecting for helvite has been complicated due to the abundance of masses of small clear garnet crystals whose color is almost identical with the brown-red helvite. Moreover both minerals have a similar hardness, are isotropic and have

similar refractive indices. Many specimens could not be identified with certainty except by gravity measurement and spectrographic analysis. These garnets are Ca-Fe garnets consisting essentially of andradite and lesser amounts of spessertite as shown by qualitative spectrographic analysis and their specific gravity, ranging from 3.80 to 3.92. All of the many garnet specimens examined contain a constant and characteristic 0.3% Sn content, which is of especial interest and is receiving further attention. The previously reported specific gravity values of helvite vary from 3.16 to 3.36. Microgravities of microscopically isolated clear fragments of the brown-red helvite here reported lie within this range. In addition to the common brown-red helvite, and the lesser abundant lemon yellow (Mn-richer) variety, a clear transparent colorless variety has also been identified by a spectrographic analysis of isolated fragments. These have the typical, somewhat greasy luster and brilliance of the colored variety of helvite. No previous record of colorless helvite has been found. Some of this colorless variety was undoubtedly mixed with the colorless fluorite-magnetite specimen in which the Be was originally discovered from this locality.

This helvite deposit is a possible commercial source of beryllium as the mineral is apparently far more abundant here than in any other locality so far reported in America, in fact helvite is one of the major minerals of a "helvite rock." This occurrence is also different, in that it lies in a contact metamorphosed limestone region of considerable extent, and the Be is apparently confined to fissure faults which acted as vents for ascending volatile magmatic products containing fluorine and beryllium which superimposed a pneumatolitic metamorphism in restricted zones on the surrounding contact metamorphism. The Be is also present as a distinct mineral and not as an isomorphous replacement of an element in other ores. The potential value as a Be ore, if future development demonstrates the presence of helvite rock in sufficient quantity, lies in the fact that its gravity is so close to fluorite, and so different from the abundant magnetite and lighter gangue minerals (calicite and feldspar) present, that it would be enriched in

the fluorspar fraction by simple gravity milling methods. The sulfide content of the helvite molecule could reasonably be expected to permit a separation of helvite from the fluorite gravity concentrate by some oil flotation process. Finally the ready solubility of helvite in strong mineral acids should offer considerable processing advantages over beryl in extracting beryllium salts and metal, especially so since beryllium can be extracted from an iron-manganese-beryllium hydroxide precipitate of the dissolved mineral by leaching with cold concentrated ammonium carbonate solution. Basic beryllium carbonate is then precipitated from the ammonium carbonate extract on boiling.

A helvite locality identical with this New Mexico one, has been described and reported in southern Norway by V. M. Goldschmidt at Hörtekollen (V. M. Goldschmidt, " Die Kontaktmetamorphose in Kristianiagebiet," Skr. Norske Vidensk. Akad. Math.-Naturv. Kl. Oslo, No. 1, p. 394–399 and 93 (1911).

This preliminary report is submitted in view of the growing interest in beryllium resources and the possible future demand for a greater domestic supply of beryllium ore. This preliminary report will demonstrate the value of spectrographic analysis in rapid systematic prospecting for new sources of strategic metals. A more detailed report will follow as part of an investigation on the geochemistry of beryllium.

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THE PROCESS OF VEIN FORMATION.

Sir: The paper by Rollin Farmin on " Host-Rock Inflation by Veins and Dikes at Grass Valley," published in the March–April, 1941, issue of your journal, records an advance in the general notions relating to the development of quartz veins. But one may wonder why, in discussing *dilatancy* and searching the literature as he does, Farmin does not take some cognizance of the work of W. J. Mead,[1] who made the principal contribution to the subject.

[1] Mead, W. J.: The geologic role of dilatancy, Jour. Geol. 33: 685–98, 1925.

Had Farmin read and appreciated the full force of Mead's argument, his views may have been modified. Possibly instead of inferring that the host-rocks were inflated by the introduction of veins and dikes, he may have reasoned that the substances which formed these veins and dikes were largely drawn into the openings where they are now found, by forces due to dilatancy, forces that were set in motion during large-scale deformation.

Farmin's work shows much real thought and originality. He defines his terms and reasons from his facts rather than down to them, nor does he strain after an exactitude in his quantitative work that the nature of the subject will not permit. His principal considerations are convincing and call for a brief discussion of some of the hypotheses that relate in general to the process of vein-formation. As Farmin says, " Any philosophy for directing mine-development must be based on a theory of ore-genesis." To work out such a philosophy and to utilize it, are indeed the chief reasons for having a geologist around a mine, if not the only reasons. Adequate explanations of the manner in which the veins were formed at any particular mine, will go far toward determining conceptions that may be logically entertained regarding the expected depth, volume and grade of the ore-shoots and give, as well, direction to the methods by which these ore-shoots may be best discovered, developed, and mined.

Farmin lays hold of one important conjecture that conforms with characteristics common to quartz-veins as they are found, not only in the Grass Valley District, but in many other gold-bearing districts of differing geologic age. From what he sees in Grass Valley, he reasons that the fractures containing the veins were no sooner formed, than the silica-bearing mediums filled them, sulphides, metallics and all, largely at one stroke. All the evidence that he cites relating to subsidiary veinlets in the walls of the main veins at Grass Valley can be paralleled in the Pre-Cambrian, for instance at the Sigma Mine in Quebec, or in the Tertiary, as at the Maguarichic Mine in Chihuahua. There can be no doubt of the aptness of his comparison of the phenomena attending the development of these veinlets with those exhibited

when cement is introduced into layers of shaly sandstone during the process of pressure-grouting of dam-site foundations through drill-holes. But in using this comparison, he should still hold in mind that in many mining districts, as he says of Grass Valley, there are continuations of "main breaks" that go on for great distances beyond the producing areas and many of these extensions do not contain appreciable amounts of quartz. The truth of this comes home to most prospectors and geologists at one time or another, particularly when they presume to follow a given trend too far. Clearly then, many other forces have taken part in forming fissures and openings in addition to the "telluric" pressures behind or within the silica-bearing mediums that in places filled them.

Any hypothesis that explains injection-phenomena in the wall-rocks and unsupported fragments of country-rock in the middle of a vein, or the interleaving of quartz and country-rock in "lit par lit" structure, must also account for vugs lined with crystals containing fluid-inclusions.[2] These are found in the veins of the same Grass Valley District that Farmin describes. In fact vugs and injection-characteristics are found together in veins that range in age from the Pre-Cambrian to the Tertiary.[3]

May there not be a more complete explanation than that advanced by Farmin? At once, when "breaks" began to form, a pull would have been set up towards the dilatant openings so formed.[4] Such forces would have operated downwards to the utmost reaches, and outward into the most minute ramifications of the fracture system. Also impelled by "telluric" pressures and gas expansion, the silica-bearing medium, liquid, gaseous,

[2] Lindgren, W.: The gold-quartz veins of Nevada City and Grass Valley districts California. U. S. Geol. Surv., 17th Ann. Rept., pt. 2, 1896. Note particularly discussion on gangue minerals, p. 114.

[3] The problem of vugs, banding and unsupported wall-rock fragments has been treated in an interesting series of experiments by Alexander MacLean of the University of Toronto, the results of which have not yet been published. It is to be hoped that the Editor of Economic Geology may induce MacLean to record his results and conclusions so that they may have the general acceptance they deserve.

[4] As John A. Dresser says, "A force much as the suction which is set up when an ordinary, rubber-sac fountain pen is filled."

mushy, as it may have been, or more likely having all three attributes, dependent upon the immediate situation, as may be inferred from varying effects of the entrance of the silica-bearing medium in different places, would have been both pulled and shot into every slightest break in the main part of the fissure system. It would no doubt also make way for itself adjacent to main breaks, by injection, as in the grouting operation, but being limited in its distribution along the strike by the amount of silica-bearing medium that was available in the ultimate source from whence it came.

Openings at the depths where quartz-veins formed, were for the most part potential. They no sooner began to be, than they were filled. If they were not filled with quartz-depositing fluids, then with differentiates, possibly dike-depositing-material, or if neither of these fluids were available, they were filled with finely comminuted rock from the walls of the openings themselves by flowage, as Farmin very accurately observes. Any region where quartz veins were forming, may be thought of, as having been heaved to and fro many times, quivering in fact. Thus, the fluids that were shot into the resultant openings have left one effect here and another there, dependent upon the differing physical and chemical environments in different places and the varying composition of the fluids as they reacted under their own inherent pressures and the tremendous pulls set up by dilatancy.

The operations of such forces are not consistent with fine-spun "paragenetic" sequences of minerals that would imply separate introduction at greatly different time-intervals. Farmin's paper closes with this statement—: "the hypothesis of a late, independent introduction of the gold, metallic sulphides, and soft gangue-minerals is inconsistent with their wide distribution throughout tremendously ramifying vein systems," and this agrees with the facts disclosed in many mine-workings in the Pre-Cambrian and Tertiary.

Still another question comes to mind. Would the fissures have reached to some distant "magmatic reservoir" for their supply of quartz-forming-fluid as most recent geological writers seem to

infer? Or may they not have extended into a nearby, partially coagulated, intrusive mass that had already reached close to surface? Thomas Belt in 1873, first showed that quartz-veins and bodies of acid, igneous intrusives are many times concurrent. Spurr carried the relation further, and Emmons has shown a world-wide relationship between the upper cupolas of batholithic bodies and quartz veins. In many districts the veins are clearly related to the settlement that followed upon the intrusion, that is, within the period when the larger, underlying masses of intrusive were still hardening into rock.

It is during this period that collecting forces due to dilatant spaces developing in the fissures, would reach out and pull on the yet unconsolidated material in the coagulating mass of the magma. Also during this period, the magma, no doubt would have developed phases differing "in composition from the solid phase as a whole, by being in general more acid and containing a larger amount of mineralizers, in short, pegmatitic or aplitic in nature,"[5] and containing the quartz-depositing mediums whose effects are under discussion. Minor amounts of basic differentiates of the opposite pole, which have so often supplied the lamprophyric dikes prevalent in gold areas, would also have been developed. Moreover, the forces of dilatancy, set up in the neighboring fissures would have lent direction to the expansive forces inherent in the fluids themselves, volatile, liquid, or viscous, as they may have been. Operated upon in this manner, not many cubic miles of cooling granodiorite would have been required to supply all the vein-quartz that could be computed as existing, in a set of fissure-veins,—in say, the Grass Valley District.

To cite another instance, this time in connection with basic intrusives—, the intimate relation between a cooling mass of peridotite and the development of asbestos veins within it, has been set out with quantitative precision in an admirable paper by R. P. D. Graham[6] on the asbestos deposits of Quebec. In these occur-

[5] Mead, W. J.: *Op. cit.*, p. 697.

[6] Graham, R. P. D.: Origin of Massive Serpentine and Chrysotile-Asbestos, Black Lake—Thetford Area, Quebec. ECON. GEOL. 12: 154–202, 1917.

rences, it should also be pointed out, that the opening of contraction cracks and faulting may have set in motion forces of dilatancy, which were thus, no doubt, important factors in causing the entrance of solutions into the minute, ramifying and intersecting fractures that are found in these deposits.

An earlier generation of geologists built up a theory of " lateral secretion " to account for veins and their metallic content. The immediate mechanisms that they imagined, have been disproven, but, at least, it would seem, they caught the great fact of a concomitant relation between certain country rocks and certain veins —possibly there may have been an underlying element of truth in their conceptions which may be utilized in a somewhat different way. Is it necessary to imagine " magmatic chambers " at great depths where it is assumed differentiation took place, as so many modern geologic writers do? Because the gold veins in a region such as the Sierra Nevada Mountains are widely distributed, the " magmatic chambers " that supplied the veins must also have been plentiful, so plentiful indeed, that if they did in fact co-exist with the upper portions of widely distributed masses of cooling, igneous rock, then there would be an explanation that takes account of the space-relations as we now see them.

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Aug. 1, 1941.

REVIEWS*

Possible Future Oil Provinces of the United States and Canada. Edit. by A. I. LEVORSEN. Pp. 154; Figs. 83. Amer. Assoc. of Pet. Geol., Tulsa, Oklahoma, 1941. Price, $1.50.

This represents a symposium conducted by the Research Committee of the American Association of Petroleum Geologists at Houston in April, 1941, to investigate the undiscovered petroleum possibilities of the area north of Mexico. P. S. Smith is responsible for Alaska and regional geological societies and National and Provincial Bureaus for the other 8 provinces, consisting of Western Canada, Pacific Coast states, Rocky Mt. Regions, Northern Mid-Continent, West Texas, Eastern Canada, Eastern United States, and Southeastern United States. Thus, behind it lies the authority of many geologists, both government and private.

Each section deals with geological sections, stratigraphy, and structure, and is illustrated by maps and sections, and accompanied by selected references. Much information is compressed into few pages and it is skillfully welded together by the editor. The book not only gives a picture of the places of future oil discoveries in this vast area, but is also a geological handbook of the areas. Credit is due to the Association for promulgating it and to the Editor for an excellent task.

Minerals Yearbook, Review of 1940. Edit. by H. D. KEISLER. Pp. 1459. U. S. Bur. of Mines, Washington, Sept., 1941. Price, $2.00.

This annual volume has been awaited with interest because of the part being played by minerals in armament and war. It embodies late information on strategic and critical minerals that have resulted from national defense activities of the Bureau of Mines and special canvasses by the Economics and Statistical Branch, such as that on magnesium and bauxite reserves. Much confidential information cannot be published because of national defense requirements, but this is made up by expansion elsewhere.

The volume is a little thinner than previous ones and, as must be expected during war time, data on the world production of many minerals is not available. It deals with the customary statistical material on produc-

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

tion, consumption, distribution, new developments, technologic advances, and economic trends, and also includes much new material relating to defense minerals and agencies, and the international situation. The charts are much improved and more domestic factual data are given than ever before.

Geology, 1888–1938. Fiftieth Anniversary Volume. Pp. 578. Geological Society of America, 1941.

The half-century celebration of the Society has produced a tangible lasting memorial in this comprehensive volume. It is a review of the development of various sciences of geology during their period of greatest construction and final formulation. This has been effectively accomplished by separate reviews of each branch by members of the Society most fitted for the task.

The following group of the subjects and authors gives some idea of the contents.

Physiography, Kirk Bryan
Glacial Geology, R. F. Flint
Oceanography, H. C. Stetson
Invertebrate Paleontology, P. E. Raymond
Vertebrate Paleontology, A. S. Romer
Prehistoric Archeology, Chester Stock
Paleobotany, E. W. Berry
Stratigraphy, R. C. Moore
Sedimentation, P. D. Trask
Structural Geology, R. D. Reed
Pre-Cambrian, M. E. Wilson
Mineralogy, Edward H. Kraus
Petrology, Adolph Knopf
Volcanology, Howel Williams
Geochemistry, Esper S. Larsen
General Geophysics, H. E. Merwin
Seismology, Beno Gutenberg
Ore Deposits, L. C. Graton
Petroleum Geology, W. B. Heroy
Exploratory Geophysics, D. C. Barton
Engineering Geology, W. J. Mead

Each author has covered the trend of fundamental advances of thought in his subject and gives a bibliography. The development of concepts and the trend of ideas, climaxing in the prevalent ones, are clearly set forth. It is material that should be read by every student of geology.

Geology of California and the Occurrence of Oil and Gas. Edit. by OLAF P. JENKINS. Pp. 276; Figs. 79. California Division of Mines, Bull. 118, San Francisco, 1941.

This valuable volume is both a textbook of California geology and of oil and gas, and a vast amount of data is assembled of the various California oil fields. The Bulletin is a pre-print of Part II of the Geologic Formations and Economic Development of the Oil and Gas Fields of California, including Chapters 4 to 7.

Chapter 4 includes Geomorphic Provinces of California and Salient Geologic Events in California and the Relationship to Mineral Deposition,

by Olaf P. Jenkins and Position of California Oil Fields as Related to Geologic Structure, by Ralph D. Reed.

Chapter 5 on the geologic history and structure includes parts on California's Record in the Geologic History of the World, by Ralph D. Reed, and Geologic History and Structure of the Central Coast Ranges of California, by N. L. Taliaferro.

Chapter 6 on the Paleontology and Stratigraphy includes 9 sections on Characteristic Fossils by G. D. Hanna and L. G. Hertlein; Foraminifera, by C. C. Church; Later Mesozoic, by F. M. Anderson; Tertiary Correlation, by B. L. Clark; Eocene Foraminiferal Correlations, by B. Laiming; Oligocene Formations by L. C. Forrest; Correlation Chart of the Miocene, by R. M. Kleinpell; Pliocene Correlation, by U. S. Grant IV and L. G. Hertlein; and The Pleistocene, by J. E. Eaton.

Chapter 7 on the Occurrence of Oil includes five sections consisting of the Los Angeles Basin, by S. G. Wissler; Santa Maria District by S. G. Wissler and F. E. Dreyer; East Side San Joaquin Valley, by G. C. Ferguson and West Side, by P. P. Goudkoff; and Origin, Migration, and Accumulation of Oil by H. W. Hoots.

Part III, to come, will contain descriptions of the individual oil and gas fields.

There are many excellent maps and line drawings which offset the poor reproduction of the halftones. Much data not heretofore available is published in this volume. The State Mineralogist and the Chief Geologist are to be congratulated for this excellent undertaking.

BOOKS RECEIVED.

WILLIAM E. BENSON.

West Part of Vauquelin Township, Abitibi County. C. TOLMAN. Pp. 19; figs. 2; maps 4, inc. 2 large geol. maps in color, scale 1″ = 1,000 ft. Quebec Bur. Mines, Geol. Rept. No. 6. Quebec, 1940. *General geology and economic geology of gold mines.*

The Mining Industry of the Province of Quebec for 1939. Pp. 128; pls. 4. Quebec Bur. Mines. Quebec, 1940. *Summary of all mineral production and reference list of companies.*

Summary of Records of Surface Waters of Washington, 1919–1935. N. C. GROVER AND G. L. PARKER. Pp. 451; pls. 7. U. S. Geol. Surv. W. S. P. 870. Washington, 1940. Price, 65 cents. *Statistical.*

Surface Water Supply of United States, 1939; Part 11, Pacific Slope Basins in California. C. G. PAULSEN and others. Pp. 438; pls. 2. U. S. Geol. Surv. W. S. P. 881. Washington, 1940. Price, 75 cents. *Statistical.*

Surface Water Supply of United States, 1939; Part 14, Pacific Slope Basins in Oregon and Lower Columbia River Basin. C. G. PAULSEN and others. Pp. 216; pls. 1. U. S. Geol. Surv. W. S. P. 884. Washington, 1940. Price, 30 cents. *Statistical.*

The Goodnews Platinum Deposits, Alaska. J. B. MERTIE, JR. Pp. 94; pls. 9; figs. 2; geol. map in color, 12″ × 17″, scale 1/62,500. U. S. Geol. Surv. Bull. 918. Washington, 1940. Price, 50 cents.

Palaeozoic Geology of the Toronto-Hamilton Area, Ontario. J. F. CALEY. Pp. 284; maps 2, inc. geol. map in color, scale 1″ = 4 miles; numerous unnumbered tables and well logs. Canada Dept. Mines and Res., Geol. Surv. Memoir 224. Ottawa, 1940. Price 75 cents. *Detailed stratigraphic description plus an interesting chapter on the mineral resources.*

Mining, Oil, and Mineral Laws of New Mexico. C. H. FOWLER AND S. B. TALMAGE. Pp. 223. N. Mex. School Mines, State Bur. Mines and Min. Res., Bull. No. 16. Socorro, 1941. Price, 75 cents. *Interesting compilation of all laws of mineral industry in the state.*

Tippah County Mineral Resources. L. C. CONANT AND T. E. MCCUTCHEON. Pp. 212; figs. 21; geol. map 15″ × 19″, scale 1″ = 1.5 miles. Miss. Geol. Surv., Bull. 42. University, 1941. *Results of surveying and testing deposits, chiefly non-metallic in character.*

Geology and Mineral Deposits of Upper Waini River, North West District. D. A. B. DAVIES. Pp. 21; geol. map in color 13″ × 19″, scale 1″ = 1.75 miles. British Guiana Geol. Surv., Bull. No. 15. Georgetown, 1940. Price, 24 cents.

Geology and Mines of the Mashaba District. R. TYNDALE-BISCOE. Pp. 8; figs. 2; geol. map 7″ × 8″, scale 1″ = 6 miles. South. Rhodesia Geol. Surv., Short Rept. No. 34. Salisbury, 1941. *Concise but complete summary of area.*

Geology and Ground-Water Resources of Lanai and Kahoolawe, Hawaii. H. T. STEARNS. Pp. 170; pls. 18; figs. 34; geol. map in color, scale 1/62,500. U. S. Geol. Surv., Hawaii Terr. Bull. 6. Honolulu, 1940. *Complete report, covering all phases of the geology. Includes chapters on geophysics by J. H. Swartz, and petrography by G. A. Macdonald. Illustrations are excellent.*

Golden Mirages. P. A. BAILEY. Pp. 353. Macmillan Co. New York, 1940. Price, $3.00. *Desert tales and legends of lost mines of the Southwest as picked up by a credulous layman. They are interesting, well-told tales, including stories about Pegleg Smith and others.*

Folk Culture of Yucatan. R. REDFIELD. Pp. 416. Univ. of Chicago Press. Chicago, 1941. *A geographical study of Yucatan which blends folk-lore, culture, history, and sociology into an interesting book.*

New Zealand Geol. Surv., Thirty-Fourth Annual Report. Pp. 15. Wellington, 1940.

Missouri Geol. Surv., Biennial Report of State Geologist to Sixty-First Assembly. H. A. BUEHLER. Pp. 48; 1 map. Rolla, 1941.

Divrik Mintakasi Turmalini Manyetit Yataklari (Tourmaline-magnetite deposits of Divrik). V. KOVENKO. Pp. 100; pls. 11; geol. maps in color. Inst. d'Etudes et Recherches Minières de Turquie. Ser. B, Mem. No. 3. Ankara, 1939. *Fifty-seven page report in Turkish followed by French translation. Describes the geology of this newly discovered iron ore deposit.*

Les Gîtes de fer de la region de Hasan Çelebi. V. KOVENKO. Pp. 20; pls. 6; figs. 1; geol. map in color, scale 1:50,000. Jour. de l'Inst. des Recherches min. en Turquie, No. 3, 1940. Ankara, 1940. *Report in Turkish with French translation. Results of survey of the continuation of the iron ore province near Divrik.*

Balya Lead Mines, Turkey. V. KOVENKO. Pp. 13; pls. 2; figs. 3. M. T. A. Mag., vol. 5, No. 4/21. Ankara, 1940. *Description of the ores of the old lead mines near Troy. Report in Turkish followed by English translation.*

El problema Petrolifero del Peru. A. JOCHAMOWITZ. Pp. 130; pls. 13; tables 12; figs. 10, inc. numerous maps. Bol. del Cuerpo de Ing. de Min. del Peru, No. 125. Lima, 1939. *Survey of oil production of Peru with attempts to develop new fields.*

Carvão de Santa Catarina. L. F. GONZAGA DE CAMPOS. Pp. 90. Inst. Nac. de Tecnologia. Rio de Janeiro, 1940. *Reprint of report on these coal deposits, originally written in 1890.*

Mining Properties and Development Work in Abitibi and Temiscamingue Counties during 1939. S. ROSS AND OTHERS. Pp. 44. Quebec Bur. Mines. Quebec. 1940.

Splint Coals of the Appalachian Region: Their Occurrence, Petrography, and Comparison of Chemical and Physical Properties with associated Bright Coals. G. C. SPRUNK, W. H. ODE, W. A. SELVIG, AND H. J. O'DONNELL. Pp. 59; figs. 38. U. S. Bur. Mines, Tech. Paper 615. Washington, 1940. Price, 10 cents.

Hydrogenation and Liquefaction of Coal. H. H. STORCH, L. L. HIRST, C. H. FISHER, AND G. C. SPRUNK. Pp. 110; figs. 31; tables 59. U. S. Bur. Mines, Tech. Paper 622. Washington, 1941. Price, 20 cents. *Part I. Reviews literature and describes liquid-phase assays of some typical coals.*

Thermodynamic Properties of Gypsum and Its Dehydration Products. K. K. KELLEY, J. C. SOUTHARD, AND C. T. ANDERSON. Pp. 72; figs. 13; tables 25. U. S. Bur. Mines, Tech. Paper 625. Washington, 1941. Price, 10 cents. *Excellent account of extensive laboratory tests and experiments with the products of gypsum.*

Marl, Tufa Rock, Travertine, and Bog Ore in Ohio. W. STOUT. Pp. 50; numerous unnumbered tables and analyses. Ohio Geol. Surv., 4th series, Bull. 41. Columbus, 1940.

Subsurface Geology and Oil and Gas Resources of Osage County, Oklahoma. H. B. GOODRICH, L. E. KENNEDY, AND O. LEATHEROCK. Pp. 27; structure contour map 20″ × 33″, scale 1″ = ½ mile. U. S. Geol. Surv., Bull. 900–F. Washington, 1940. Price, 50 cents. *Part 6– region northwest of Bartlesville, townships 28 and 29 N, ranges 9 to 11 E.*

Subsurface Structure in Part of Southwestern New York, and Mode of Occurrence of Gas in the Medina Group. G. B. RICHARDSON. Pp. 23; pls. 4; numerous well records. U. S. Geol. Surv., Bull. 899–B. Washington, 1941. Price, 30 cents.

SCIENTIFIC NOTES AND NEWS

SOCIETY OF ECONOMIC GEOLOGISTS ANNUAL MEETING.

The Society of Economic Geologists will meet with the Geological Society of America, the Mineralogical Society, and the Paleontological Society in Boston, Massachusetts, on December 29 to 31, 1941.

In addition to its own sessions, joint meetings with both the Geological Society and the Mineralogical Society are planned.

Abstracts of papers, not to exceed 250 words in length, should be in the hands of the Chairman of the Program Committee (Professor H. E. McKinstry, Science Hall, University of Wisconsin, Madison, Wisconsin) by November 15, in order to be printed in advance of the meeting. Abstracts should be submitted in duplicate on blanks that will be furnished by the Chairman of the Program Committee or by the Secretary on request.

If you plan to give a paper, please communicate with Professor McKinstry at once.

M. K. SHALER is now with New Consolidated Goldfields, Ltd., in Johannesburg, South Africa.

M. F. COOLBAUGH, president of the Colorado School of Mines, has been reappointed to the Colorado State Mineral Resources Board.

ING. GUSTAVO SERRANO is the new president of the Mining Association of Mexico.

E. B. PEHRSON has been appointed chief of the economics and statistics branch of the U. S. Bureau of Mines.

S. L. BOWDITCH is geologist for the Bauxite Mining Corp., Little Rock, Arkansas.

C. A. LOGAN of the California State Division of Mines is in charge of survey and classification for mineral possibilities of a million acres of state lands in Southern California.

R. C. ALLEN of Cleveland has returned to his former position with the O. P. M. in Washington.

F. A. WADE has returned from the Antarctic to the department of geology of Miami University, Oxford, Ohio.

G. F. BROWN is assistant geologist in the division of ground water of the U. S. Geological Survey at Santa Barbara, California.

JAMES BOYD, former associate professor of geology at the Colorado School of Mines, has been called to active duty with the Commodities Division in the office of the Under Secretary of War.

P. D. WILSON, vice president of Pardners Mines Corp., recently returned from Cuba where he has been directing the development of the nickel properties of the Nicaro Nickel Co.

F. W. FARWELL has returned to Leonia, New Jersey from his position as assistant geologist for American Smelting and Refining Co., Minas Tecolotes y Anexas, Santa Barbara, Chihuahua, Mexico.

S. O. REICHERT is assistant geologist for Tennessee Coal, Iron and Railway Co. of Birmingham, Alabama.